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FROST DURABILITY OF CLAY BRICKS - EVALUATION CRITERIA AND QUALITY CONTROL

Proceedings of the CBAC/DBR Manufacturers' Symposium
March 7-8, 1984

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SUMMARY OF RESULTS

- Quality of presently produced bricks varies from plant to plant, and within each plant. The variation is mainly due to fluctuation in raw material composition and heat gradient in the kilns, and the difference in manufacturing method.

- Present durability standards for clay bricks are questionable.

- Durability of bricks is related to its saturation coefficient, specific surface area and pore structure. Firing is an effective means of modifying these properties.

- Freezing expansion is a valid test for the assessment of relative durability of clay bricks. This method can be simplified by determining the residual expansion.

- Freezing behaviour of bricks differs according to the forming method. There seems to be a critical degree of water content in the extruded bricks, above which bricks would be more susceptible to frost damage.

- Composite relationship of specific surface area and saturation coefficient is an indication of the optimum condition of firing bricks. This critical heat work, i.e., combination of temperature and soaking time profile, is a function of the composition of the raw material.

- The time to carry out the present quality control tests can be reduced by using short-term absorption tests and the accuracy can be improved if both absorption and saturation coefficient results are used in conjunction.

PREFACE

The results from the Industrial Research Fellowship Program sponsored jointly by the Clay Brick Association of Canada and the Division of Building Research from 1978 to 1982 are summarized. These results were contained in eight DBR Special Reports prepared by J.H. Kung, the Clay Brick Fellow. Information pertinent to the manufacturers is presented and those techniques suitable for plant quality control are also described. It is hoped that the information will help the plant personnel of the brick industry to better understand the material properties and the frost resistance of clay bricks.

C.B. Crawford
Director, DBR/NRC

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I. INTRODUCTION

The Problem

In Canada the principal cause of deterioration of masonry is the freezing and thawing of clay bricks in the presence of moisture. Repairs are costly and there is no assurance that deterioration will not recur. Although present brick specifications contain durability criteria, tests are time-consuming and the results are not reliable. There is little soundly-based guidance to help manufacturers improve their products, to aid designers or contractors in choosing suitable bricks, or to enable standards writing committees to specify minimum requirements for desired performance.

The Fellowship Program

A CBAC/DBR Industrial Research Fellowship Program was started in 1978 to investigate the durability of clay bricks and the causes of failure, to identify the pertinent physical and mineralogical properties that are responsible for failure in order to establish criteria for product improvement, to improve quality control, and to provide a better and faster test for the durability of clay bricks.

The program consisted of a study of nine types of commercially marketed clay bricks manufactured by six plants. These plants produce about 50% of the bricks made in Canada. The bricks were chosen mainly on the basis of their performance in service. Other important considerations were the raw materials, manufacturing process and heat gradient in the kiln. The program was divided into four phases:

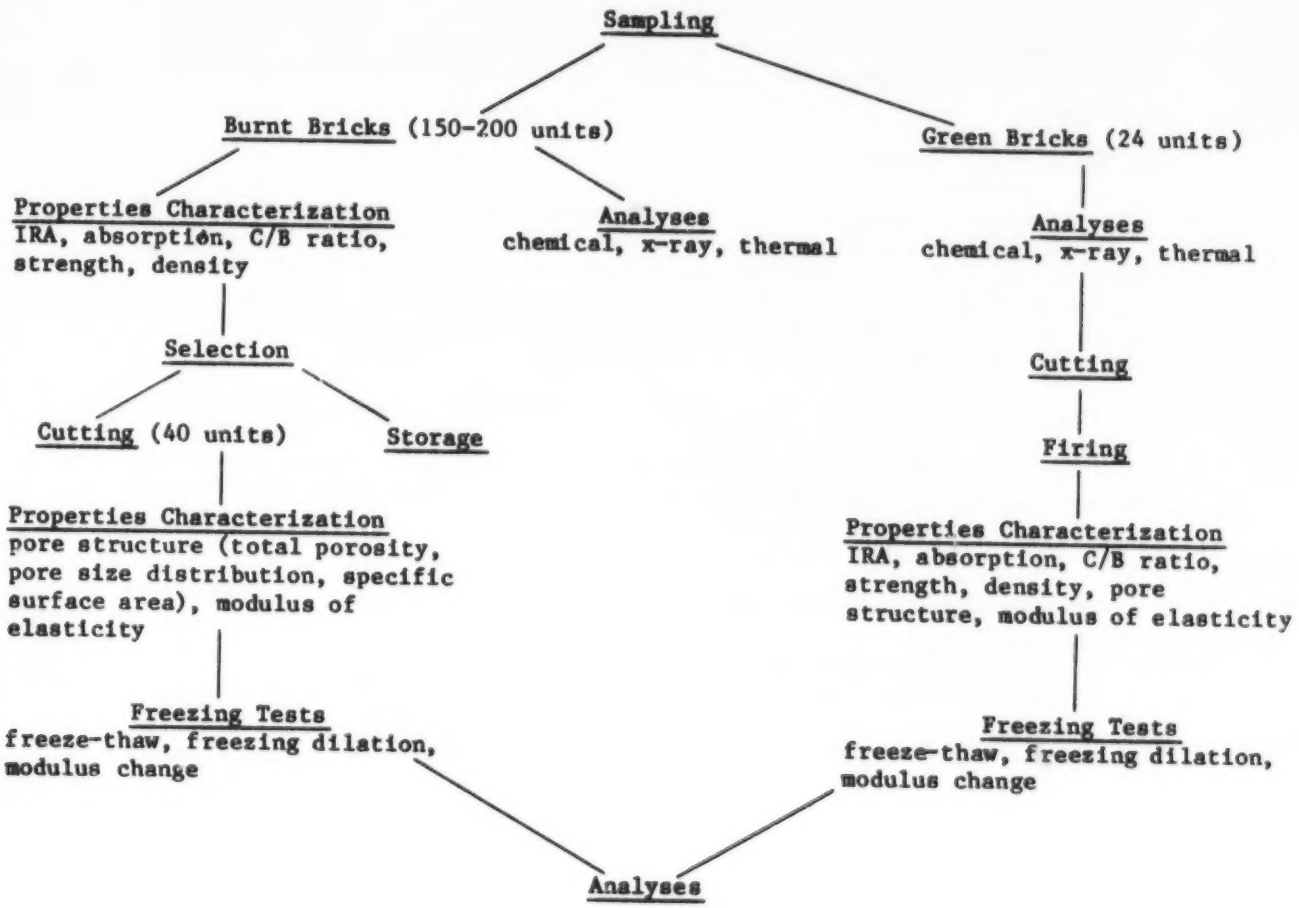
1) familiarization with literature and brick plants
2) sampling
3) characterization and testing of bricks
4) development of techniques for determining durability

The general experimental procedure followed is shown in Table 1.

TABLE 1

EXPERIMENTAL PROCEDURE

Each project of the program follows the flow chart of experiments and analyses presented below



II. SAMPLING

Prior to sampling, a comprehensive literature review was carried out and thirteen plants across Canada were visited. Consultations with various manufacturers were held and a preliminary testing of 500 bricks obtained from various sources was carried out.

The experimental work began with the sampling of products from brick plants and the documentation of the manufacturing processes. Since only a particular batch of bricks manufactured from a specific production run was sampled, the day-to-day variations in the manufacturing process were not studied. Most production runs from which test bricks were obtained appeared to be representative of normal production for the particular plant. In some cases, sampling had to be repeated due to abnormalities, such as excessive cracking in the extruded column and slowdowns in kiln schedule. A listing of the variables recorded during plant sampling is shown in Table 2.

About 200 bricks were sampled for each run and green bricks were also included. Green bricks were sampled at the end of the forming process, some prior to and some after drying. Burnt bricks were collected just before packaging. The entire manufacturing process up to forming was monitored and documented for at least two hours before green bricks were chosen for testing in order to ensure "representative" samples. Whenever possible, the kiln car of the best top condition was selected and the history of the car followed and documented. Both green and burnt bricks were sampled from the selected car. The sampling procedure for the burnt bricks took into account the different degrees of firing associated with the temperature gradient of the kiln. Firechek keys were used to determine the degree of heat work, i.e., the time/temperature profile of the firing curve, on the sampled bricks. The higher the key reading (BRI), the greater the resulting heat work.

The names of the manufacturers and the types of bricks chosen for this study are given in Table 3. In the study, bricks were identified only by code letters.

TABLE 2

LIST OF PROCESS VARIABLES STUDIED DURING PLANT SAMPLING

PRODUCT:
DATE:

PLANT:
COLLECTED BY:

A. Field Data:

Sample No.
Raw Materials
Location of Deposit
Description of Deposit

B. Processing Data:

Sample No.
Mix Formula
Additives
Grinding Proc./Equip.
Screens
Particle Size
Moisture
Comment

C. Forming:

Sample No.
Tonnage
Water
Consistency
Admixture
Vacuum
Oil Pressure
Power
Penetrometer
Moisture
Comment

D. Drying:

Sample No.
Push Rate
Dryer No.
Temp.
RH
Moisture
Strength
Shrinkage
Comment

E. Firing:

Sample No.
Push Rate
Kiln No.
Firing Curve
Atmosphere
Fuel
Shrinkage
Comment

TABLE 3

BRICKS STUDIED IN THE CBAC/DBR FELLOWSHIP PROGRAM

Brick Type	Manufacturer
Bluesteel Hand-Mold	Canada Brick, Streetsville, Ontario
Buffpress	Toronto Brick, Toronto, Ontario
Chipman Red Smooth	L.E. Shaw, Chipman, N.B.
John Price No. 60	Toronto Brick, Toronto, Ontario
Northern Lite Oriental	Toronto Brick, Toronto, Ontario
Regency Red Bark	Canada Brick, Burlington, Ontario
Rideau Red Smooth	Domtar, Ottawa, Ontario
Sand Brushtex & Bark	Canada Brick, Burlington, Ontario
Variegated Brown Antique	IXL, Edmonton, Alberta

III. LABORATORY FIRING OF GREEN BRICKS

Because it was desirable to study the behavior of the same bricks over a much wider range of properties, laboratory-fired samples were included in the experimental program. In this way, a large number of samples could be quickly produced covering the range from badly underfired to overfired, enabling comparison of bricks of different raw materials or forming methods subjected to equal heat treatment. The sampled green bricks from the plants were used as the starting materials for the laboratory firing program so that the final products could simulate the plant samples as closely as possible. The plant sampling program covered only bricks from one production run.

The green bricks obtained during the plant sampling period were sealed in plastic bags and taken to the DBR laboratory where the two ends of the brick were sliced and then cut with a band saw into bars of approximately 16.5 × 16.5 × 100 mm (0.65 × 0.65 × 3.94 in.). The cut samples were stored in a room controlled at 21°C (70°F) and 40% RH. In the laboratory firing program each type of brick underwent seven or eight different heat treatments. These firing schedules had identical firing and cooling profiles below 900°C (1652°F) and differed mainly in the temperature used in the two-hour soaking period. The eight firing curves with their respective soaking temperature and the corresponding index of heat work in the arbitrary BRI unit for firechek keys are shown in Figure 1. The reproducibility for identical programmed firing curves was ±1 BRI unit.

The laboratory-fired specimens were found to be similar and representative in properties to the corresponding plant products in most cases, and provided a series of samples of graded durability that helped to evaluate the test methods. They also provided the basis to establish a new methodology for determining the optimum firing conditions for a given brick, and to assess quickly and economically the effects of variations in the raw materials.

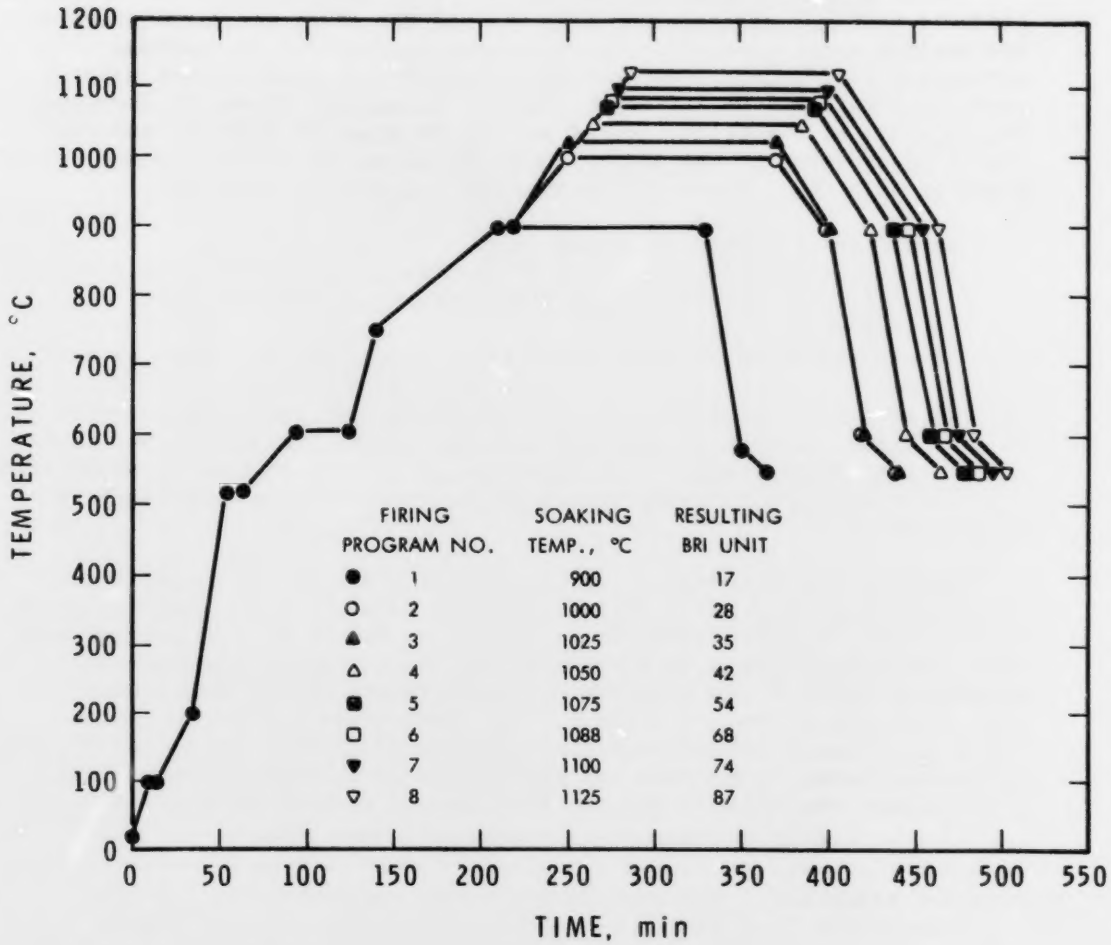


FIGURE 1

LABORATORY FIRING CURVES FOR SAMPLED GREEN BRICKS

BR 6193-32

IV. ASSESSMENT OF THE QUALITY OF BRICKS

Table 4 shows the results of grading the plant samples from all nine products studied, according to ASTM C62 and CSA A82.1 standards based on the maximum water absorption for five-hour boiling and the maximum saturation coefficient, respectively. Differences were evident between products obtained from different plants. Except for BP and ZD products, the majority of the bricks tested met the MW grade of ASTM C62 and the Type 1 requirement of CSA A82.1. Only the AZ and VD production met the SW grade of ASTM C62. These differences are mainly attributed to:

1) different degree of firing
2) properties and composition of the raw materials (Figures 2 and 3), especially the silica and lime content, as well as their property
3) manufacturing methods, e.g., stiff extrusion, dry press or soft mud
4) particle size (Figure 4); it was found that raw materials with higher content of clay had a higher proportion of fine particles than bricks made of raw materials consisting of shales, which seem to contribute toward higher saturation coefficient in the burnt brick

In general, there was a significant variation in the properties of bricks produced by a given plant. The main cause is the thermal gradient in the kilns, as illustrated as an example in Figure 5. The average heat work, the range of heat work measured and the estimated temperature difference based on the firechek key measurements of the nine production runs studied are shown in Table 5. The temperature difference in the kilns investigated ranged approximately from 30 to 75°C (86 to 167°F), the difference being larger when the kiln was fired to higher temperatures, e.g., higher heat work or BRI key measurement, as seen in Figure 6.

TABLE 4

PERCENTAGE OF BRICKS SAMPLED MEETING THE VARIOUS GRADES BASED ON ABSORPTION AND SATURATION COEFFICIENTS

	ASTM C62 % of the Bricks			CSA A82.1 % of the Bricks	
Project	SW[1]	MW[2]	NW[3]	Type 1[4]	Type 2[5]
HC	13.0	75.4	11.6	88.4	11.6
R	10.0	90.0	-	100.0	-
UCS	28.6	71.4	-	100.0	-
BP	-	23.7	76.3	23.7	76.3
ZD	-	27.4	72.6	27.4	72.6
AZ	100.0	-	-	100.0	-
VD	98.6	1.4	-	100.0	-
RG	55.6	44.4	-	100.0	-
NW	3.9	87.4	8.7	91.3	8.7

	Maximum 5-h Boiling Absorption, %	Maximum Saturation Coefficient
1. SW:	20.0	0.80
2. MW:	25.0	0.90
3. NW:	no limit	no limit
4. Type 1:	25.0	0.90
5. Type 2:	no limit	no limit

TABLE 5

HEAT WORK MEASUREMENTS IN INDUSTRIAL KILNS

Project	Average Heat Work, BRI	Range-Measured Heat Work, BRI	Estimated Temperature Difference °C
HC	81	< 69-92*	~60*
R	60	46-83	50
UCS (small kiln)	82	57-99	75
UCS (large kiln)	71	58-87	50
BP	56	42-71	50
ZD	57	48-66	40
AZ	84	55-94	75
VD	77	62-97	60
RG	54	47-63	30

* Keys corresponding to coolest regions in kiln broke, thus no actual readings were obtained near the lower extreme.

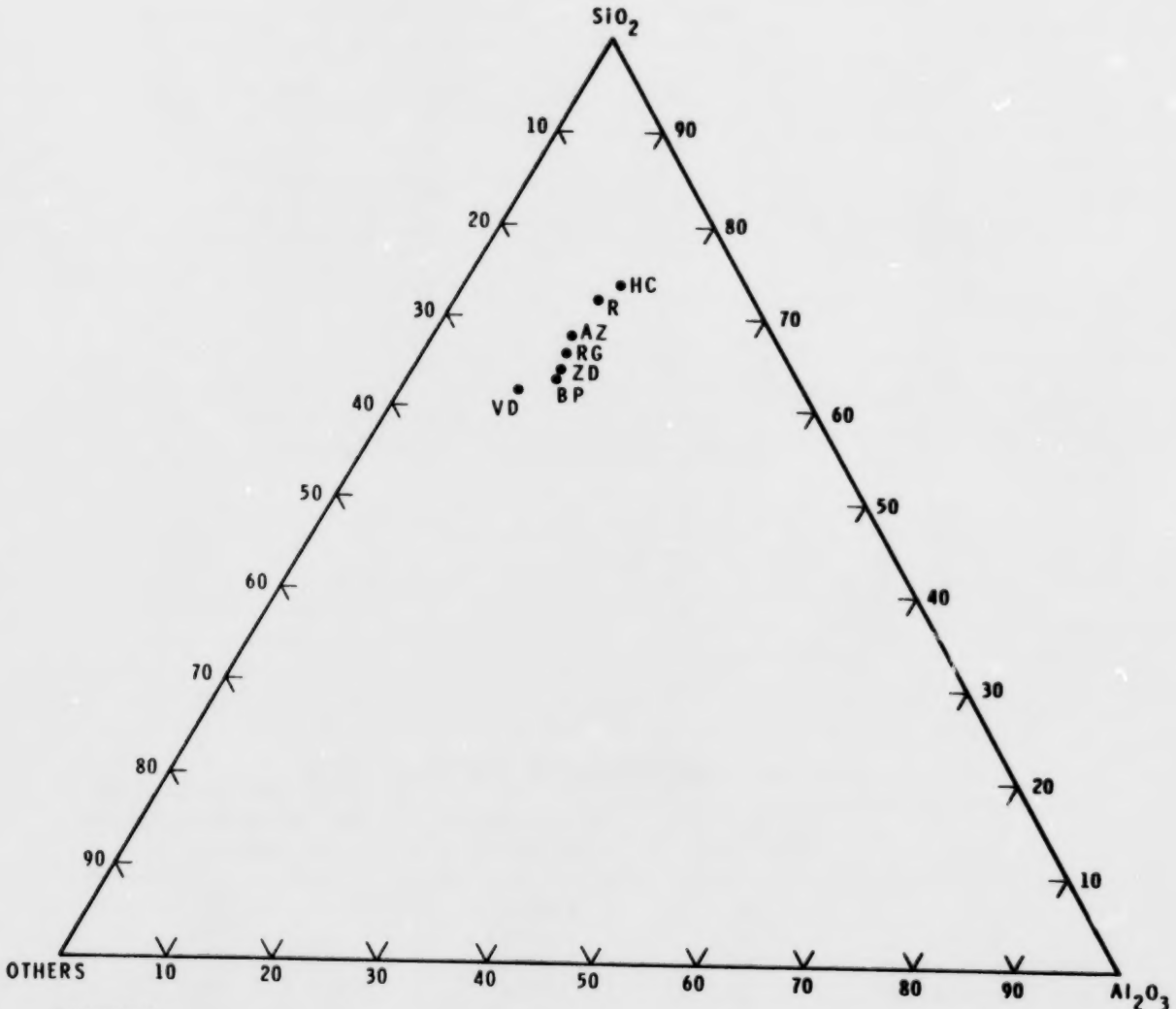


FIGURE 2

CHEMICAL COMPOSITIONS OF UNFIRED BRICKS DETERMINED BY ATOMIC ABSORPTION

BR 6277-1

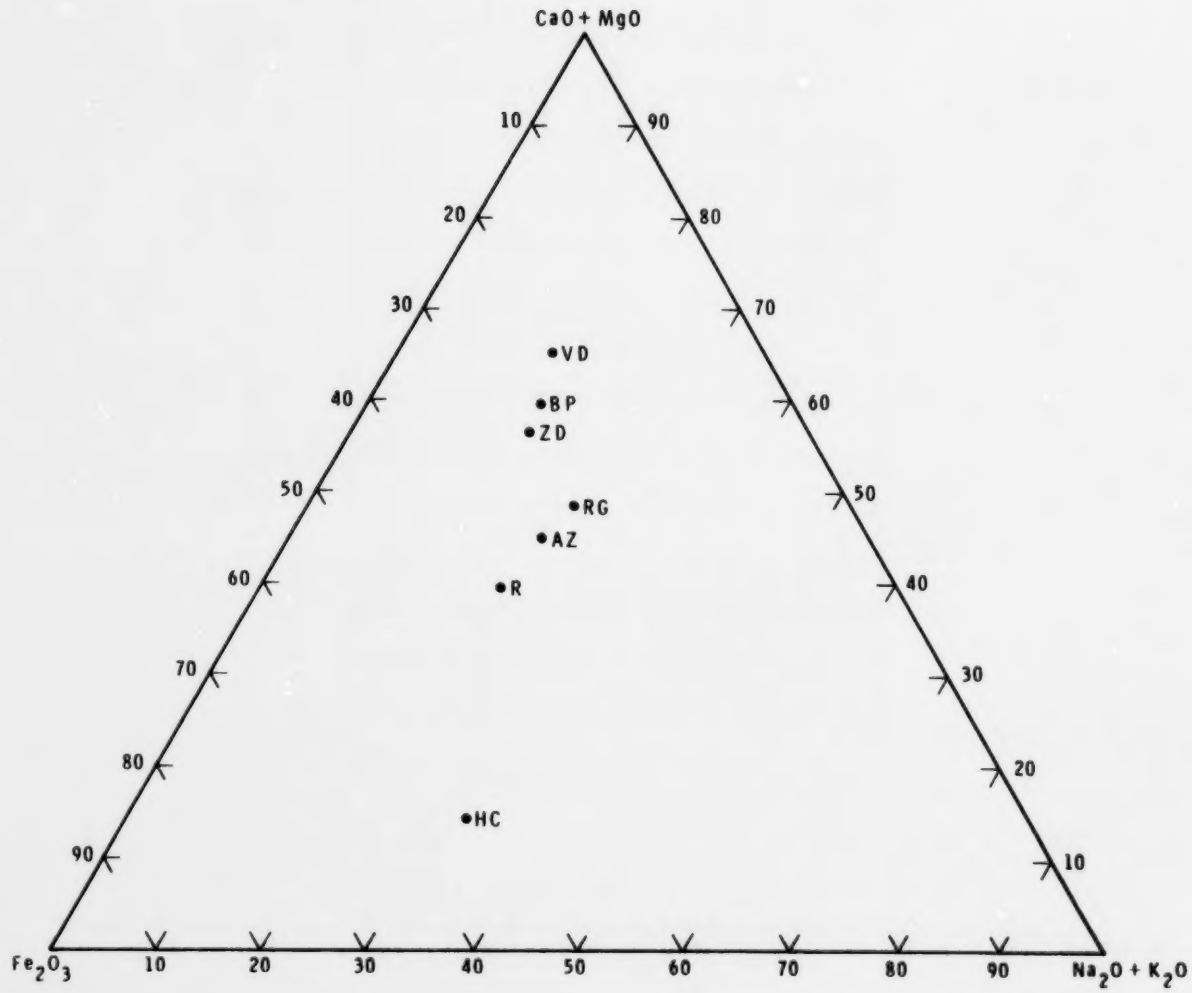


FIGURE 3

MINOR CONSTITUENTS OF THE UNFIRED BRICKS DETERMINED BY ATOMIC ABSORPTION

BR 6277-3

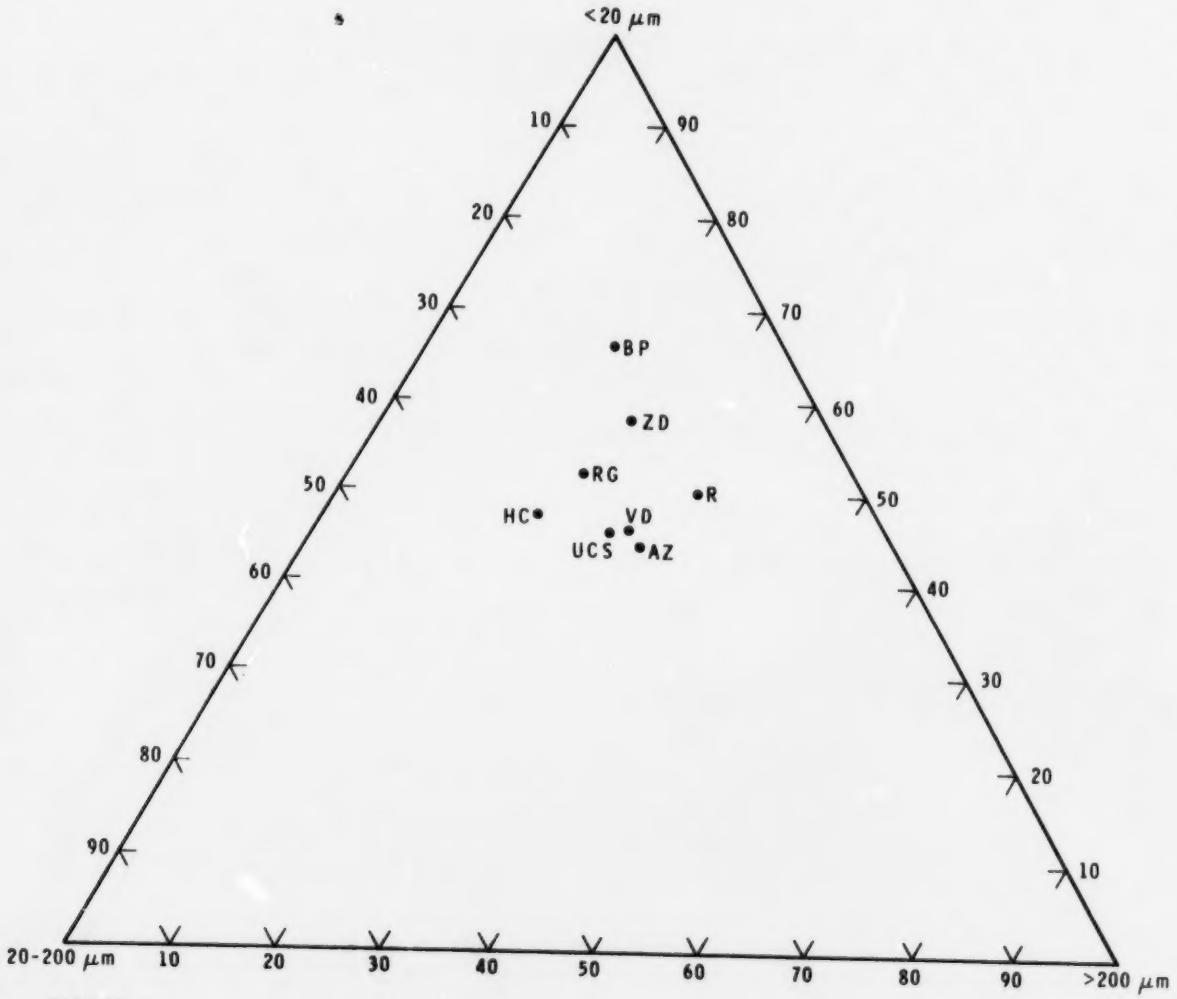


FIGURE 4
PARTICLE SIZE DISTRIBUTION OF UNFIRED BRICKS

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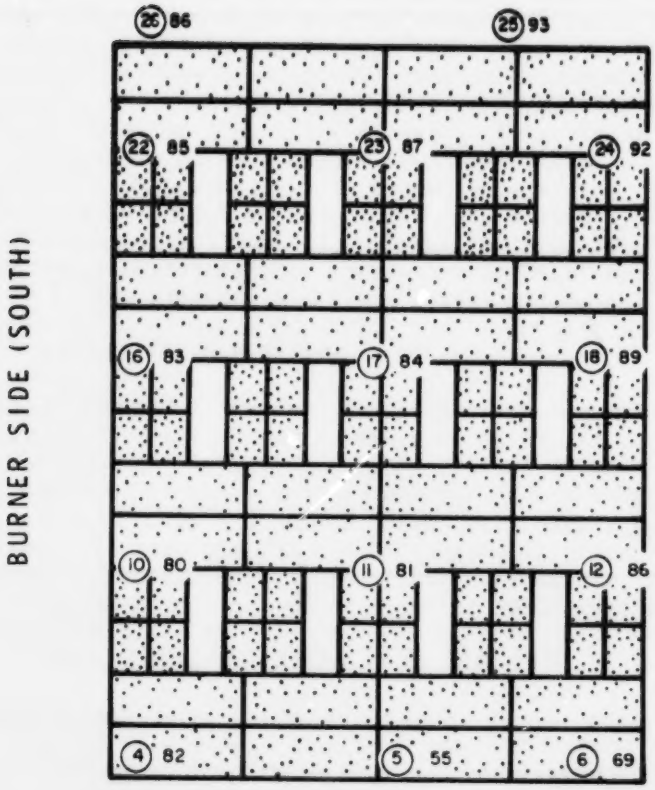

FIGURE 5

THERMAL GRADIENT IN INDUSTRIAL BRICK KILN MEASURED BY FIRECHEK KEYS EXPRESSED IN BRI UNIT

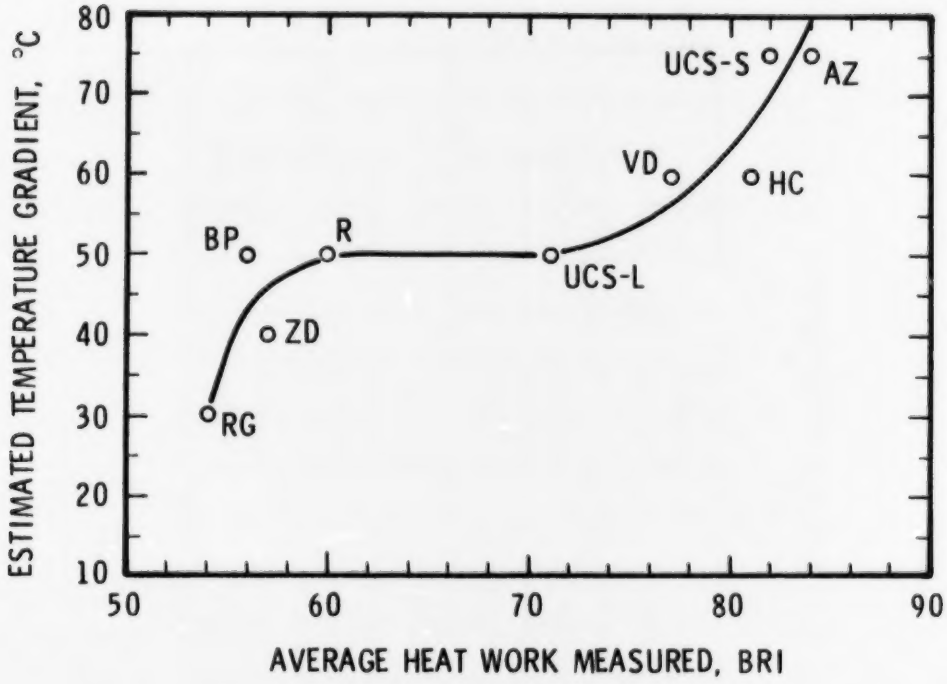

FIGURE 6

TEMPERATURE GRADIENT IN INDUSTRIAL KILNS AS A FUNCTION OF THE AVERAGE OPERATING HEAT WORK

BR 6465-1

V. FROST DURABILITY OF CLAY BRICKS

Observation of frost damage in masonry buildings seems to suggest that the performance of a building material is a function of the characteristics of the material and the microenvironment of the particular area on the building. Since the production methods yield bricks with different properties, bricks may be expected to perform differently under the same climatic exposure conditions. Similar bricks may also exhibit different durability due to the variation in the severity of the microenvironment to which they are subjected. Thus, field performance is not an absolute measure of the durability of materials, but suitable tests can rate the relative durability. In order to determine the validity of a testing method, it is useful to have suites of samples of known relative durability characteristics. In this program, sets of samples with a range of durability characteristics were obtained from plant produced products, the laboratory firing program, and field survey trips.

Comments on Standards for Durability

The present CSA A82.1 standard is of questionable value. Although the saturation coefficient criterion has some merit, it fails, by itself, to take into account the variation in the critical saturation coefficient from one raw material to the other, as has been found in this program (see Section VII, p. 35). Some underfired bricks will have a low saturation coefficient and will pass the CSA specification, although they may not possess adequate durability characteristics. The waiver clause based on compressive strength is not supported from the results of this program. However, the waiver based on absorption is statistically significant, although not totally correct.

Pertinent Properties

The microstructural properties that may be pertinent to the durability characteristics of clay bricks are: saturation coefficient, specific surface area and pore structure (total porosity and pore size distribution).

Saturation coefficient. Saturation coefficient, which is the ratio of the twenty-four hours cold water absorption value over the five hours boiling absorption value, is an approximate indication of the space available in the brick to accommodate the expansive pressure of freezing of water; i.e., the lower the saturation coefficient the more space there is for the freezing pressure to be relieved, thus it is less likely for the brick to be damaged.

Specific surface area. Specific surface area is defined as the total surface area per unit weight of the material, usually expressed as cm^2/g or m^2/g. The specific surface area of a nonporous solid, then, is the external surface area divided by the weight. In the case of a porous material such as brick, the specific surface area is given by the total sum of external and internal surface areas (such as the area comprised by the walls of pores) divided by the weight of solid.

The usual procedure for specific surface area determination of solids is based on the Brunauer-Emmett-Teller (BET) multimolecular theory of adsorption of gases.[1] The theory allows the surface area to be deduced from measurement of the amount of an adsorbate gas of known molecular size that just covers the total surface of the solid with a "monolayer". Different adsorbates may be used, water and nitrogen being the most common for ceramics and clays. Depending on the materials, for example some clays, the surface area calculated can differ drastically, depending on whether water or nitrogen is used as adsorbate gas. With burnt clay bricks, however, both yield similar values, as indicated in Table 6. For water adsorption method the instrumentation is simple, consisting of a glove box and an analytical balance; however, the control of the experimental environment is critical and the experiment may require a long waiting period for equilibrium conditions to be achieved. But many samples can be determined simultaneously, the size of the glove box being the only limitation. Special equipment is required for nitrogen adsorption method. Although only one sample can be measured at a time, results can be obtained in minutes on apparatus such as the one used in this program, which is based on dynamic flow principles.

Generally the specific surface area is determined using particles of the material. In materials with low specific surface such as a well burnt brick, particle size exerts a definite effect on the surface area measured, as shown in Table 7. The smaller the particle size used, the higher is the specific surface area for a particular weight. Thus, based on results from Table 7 for burnt bricks, granules less than 0.5 mm or 0.02 in. (minus 30 mesh) in diameter should not be used for surface area determination because the size effect becomes pronounced. Particles of minus 8 mesh and plus 12 mesh are recommended. Porosity also has an influence on the surface area measurement. Since higher porosity means more internal surface, the same material with higher total porosity will have a higher specific surface area. At equal porosity, a larger volume of small size pores results in higher specific surface than the same solid with a larger volume of coarser pores.

Since clay bricks are made of consolidated finely ground shales or clays, the unburnt green bricks have a relatively high surface area as shown in Table 8. The specific surface of most green bricks studied is approximately 20 m^2/g based on nitrogen sorption method, which is approximately the area of seventeen football fields in a single unburnt brick of weight 2.5 kg (5.5 lb). As the green brick is fired in the kiln, the particles form bonds and the specific surface area is reduced. Typically, the specific surface area of burnt Canadian clay bricks is between 0.5 to 2.0 m^2/g.

Dr. Litvan of DBR found that specific surface areas of twenty-seven bricks collected from different buildings correlate well with their field performance, as shown in Table 9.[2] Further results from the fellowship research indicate that durability can be assessed on the basis of specific surface area measurement. This is a particularly good method for bricks made from the same raw material. But the effect of raw materials must be considered. The relative durability of bricks manufactured from raw

materials of different composition cannot be predicted solely on the basis of a direct comparison of the absolute value of the specific surface area. However, specific surface area is useful for quality control purpose.

Pore structure. Pore structure has a considerable influence on many properties of porous materials. For example, strength and hardness are closely related to the total porosity of materials, as shown in Figure 7. Permeability and drying and wetting behaviour of a material are also influenced by the total porosity and pore size distribution. There are numerous references in the literature concerning durability of porous building materials stating that coarse pores (greater than 1 micron) enhance durability and intermediate pore sizes (say, between 0.1 and 1 micron) are detrimental to frost resistance. In natural weathering exposure, coarse pores are rarely full of water because although water easily fills them, they also dry out quickly. Small pores do not fill or dry easily. Water in small pores does not freeze until quite low temperatures and, therefore, has less effect on frost susceptibility of bricks. Intermediate pores are most susceptible to freeze-thaw action since the drying rate of water in them is slower than in larger pores and they are most frequently filled with water in service.

The porosity of bricks can be determined by high pressure mercury intrusion porosimetry which measures sizes of pores ranging from 0.1 mm to 0.003 micron diameter. If the pores of a material are assumed to have a simple shape, i.e. cylindrical pores, then the Laplace-Kelvin equation can be used to relate pore size to intrusion pressure. Thus by measuring the volume of mercury intruded for a given change in applied pressure, the amount of pore volume at the corresponding pore diameter can be calculated.[3]

The pore structure of clay brick is affected by many variables such as the chemical composition of the raw materials, the water content during forming, the amount of combustible matter, the particle size distribution, the pressure during forming, shrinkage and expansion characteristics upon drying and heating and the heat treatment during fabrication. Although the total porosity of unburnt bricks does not appear to be greatly dependent on the manufacturing method (Table 10), the pore size distribution is related to the forming method. In general, the greater the consolidation force during forming, the higher the percentage of smaller pores (Figure 8). Thus, stiff extrusion produces bricks with high volume of smaller pores in green state and dry press results in a more uniform and wider range of pore sizes. It is also safe to conclude that the greater the power of the extruder, the larger the volume of smaller pores (Table 10).

Two phenomena occur as the brick is fired. First, grain growth is observed as particles fuse together. This growth reduces the void space among the particles, decreasing the total porosity. Secondly, as the firing temperature increases coarsening of the pores takes place (Figure 9). Both phenomena are accelerated when liquid phase sintering occurs. Regardless of the composition of the raw materials, pore structure changes with firing. However, greater change can be induced by

heat in certain shales than others. The higher the limestone content in the raw materials, the higher is the final porosity in the burnt bricks. Surface texture has an influence on the pore structure, apparently more so on the total porosity than the pore size distribution. One would expect a much more open pore structure with a higher proportion of large pores in a rough bark texture than in a smooth texture. However, this was not the case. The bark texture had almost twice as much porosity as the smooth texture (Figure 10), but the pore size distributions were nearly identical (Figure 11).

Pore structure and the saturation coefficient are interrelated. The saturation coefficient is directly proportional to the amount of the intermediate pore sizes of the brick, as illustrated in Figure 12. In general, large pores lower the saturation coefficient, whereas small pores increase it.

In comparing the various water absorptions results and the porosity determined by the mercury intrusion porosimetry, the following important conclusions can be drawn. Firstly, some bricks are easier to saturate than others. For example, in the same one-hour soaking in water, bricks from projects BP and NW achieved the highest level of saturation, e.g., 80%; whereas, HC and VD bricks had the lowest degree of saturation, e.g., below 60%. The rest fall between these values. Secondly, brick samples fired at higher temperatures (of greater frost resistance) are more difficult to saturate by soaking in water than those fired at lower temperatures. Such different rates of water uptake have an important practical significance in considering the weatherability of bricks in exposed masonry structures and should be further explored.

Heat work, i.e., the combined effect of peak temperature and soaking time, is the most effective means to modify and improve the important durability related properties (saturation coefficient, specific surface area and pore structure), as shown in Figures 13-15. As these properties are functions of the raw material composition, it is unlikely that a universal standard for durability can be established that is applicable to all bricks made of different materials. However, individual quality control requirements can be established for each family of bricks manufactured from the same source of raw materials on the basis of these characteristics.

TABLE 6

COMPARISON BETWEEN NITROGEN AND WATER SURFACE AREAS

Brick Specimen	Surface Area m^2/g	
	Nitrogen	Water
LBW	9.88	10.72
B1	0.61	1.11
D-3-1	0.10	0.10
9-2-3	0.15	0.14
9-4-5	0.17	0.15
1-1-1	0.23	0.32
7-3-1	1.65	1.64

Linear Regression Analysis:
Water Surface Area = 0.0555 + 1.078 (Nitrogen Surface Area)
Correlation Coefficient = 0.99882

TABLE 7

PARTICLE SIZE EFFECT ON MEASURED SURFACE AREA

Brick Specimen	Particle Size	Nitrogen Surface Area m^2/g
IS-3-2A	-8/ +12 mesh	0.06
IS-3-2A (repeat)	-8/ +12 mesh	0.06
IS-3-2B	-12/ +30 mesh	0.08
IS-3-2C	-200 mesh (ground in a Bleuler pulverizer for 2 min.)	1.06

TABLE 8

NITROGEN SURFACE AREA OF GREEN BRICKS

Project	Specific Surface Area, m^2/g
HC	13.11
R	13.45
UCS	16.98
BP	18.11
ZD	17.19
AZ	18.70
VD	16.59
RG	20.83

TABLE 9

SURFACE AREA OF BRICKS RELATED TO FROST DURABILITY

Sample No.	Area m^2g^{-1}	Field Performance		
		Durable	Questionable	Unsound
26	0.21	+		
23	0.35	+		
19	0.45	+		
13	0.52	+		
3	0.57	+		
17	0.63	+		
7	0.76	+		
18	0.78		+	
15	0.85	+		
22	0.98	+		
9	1.01			
14	1.01	+		
8	1.11	+		
6	1.14			+
12	1.25	+		
4	1.35			+
2	1.44			+
11	1.46		+	
21	1.50			+
1	1.65			+
27	1.68			+
25	2.00			+
10	2.65			+
16	2.88			+
5	3.00			+
24	5.60			+
20	8.25			+

(Litvan, 1975)

TABLE 10

PORE STRUCTURE OF GREEN BRICKS

Brick	Total Porosity, %	Median Pore Diameter, um	Forming Process
1	24.5	0.13	Dry Press
2	22.0	0.18	Soft Mud
3	21.2	0.15	Extrusion, F-R-H
4	19.3	0.12	Extrusion, Steele 60
5	19.3	0.06	Extrusion, Steele 90
6	19.8	0.07	Extrusion, Steele 90
7	20.6	0.05	Extrusion, Steele 90
8	22.8	0.06	Extrusion, Steele 90

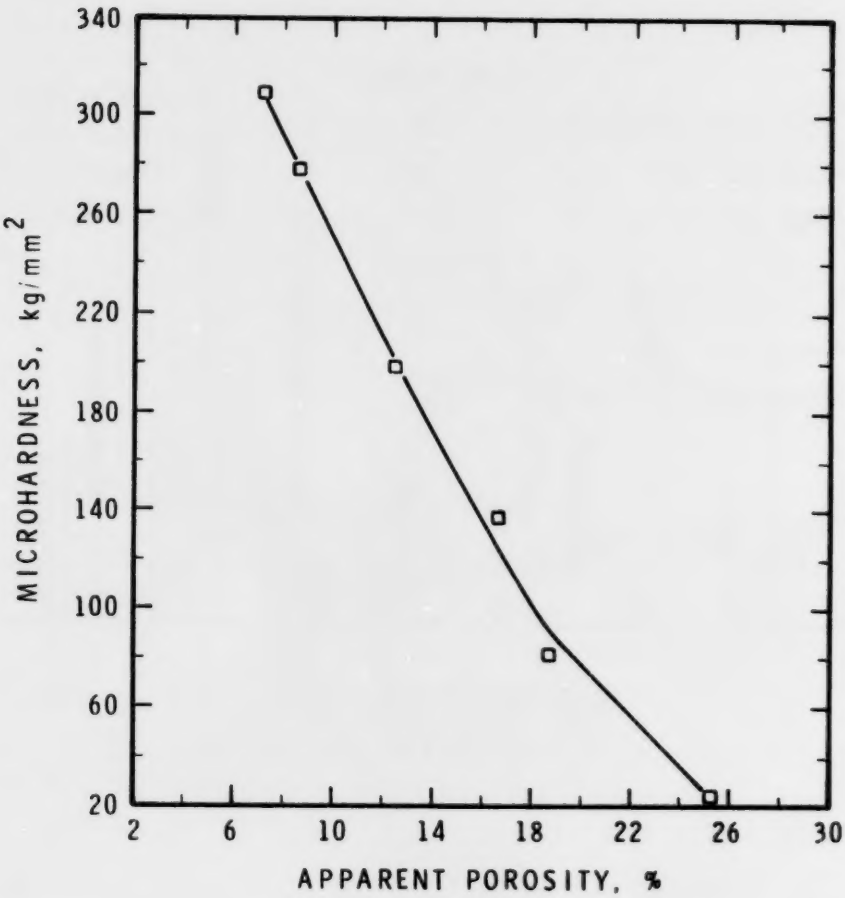

FIGURE 7

MICROHARDNESS OF BRICKS FROM PROJECT HC AS FUNCTION OF APPARENT POROSITY

BR 6465-2

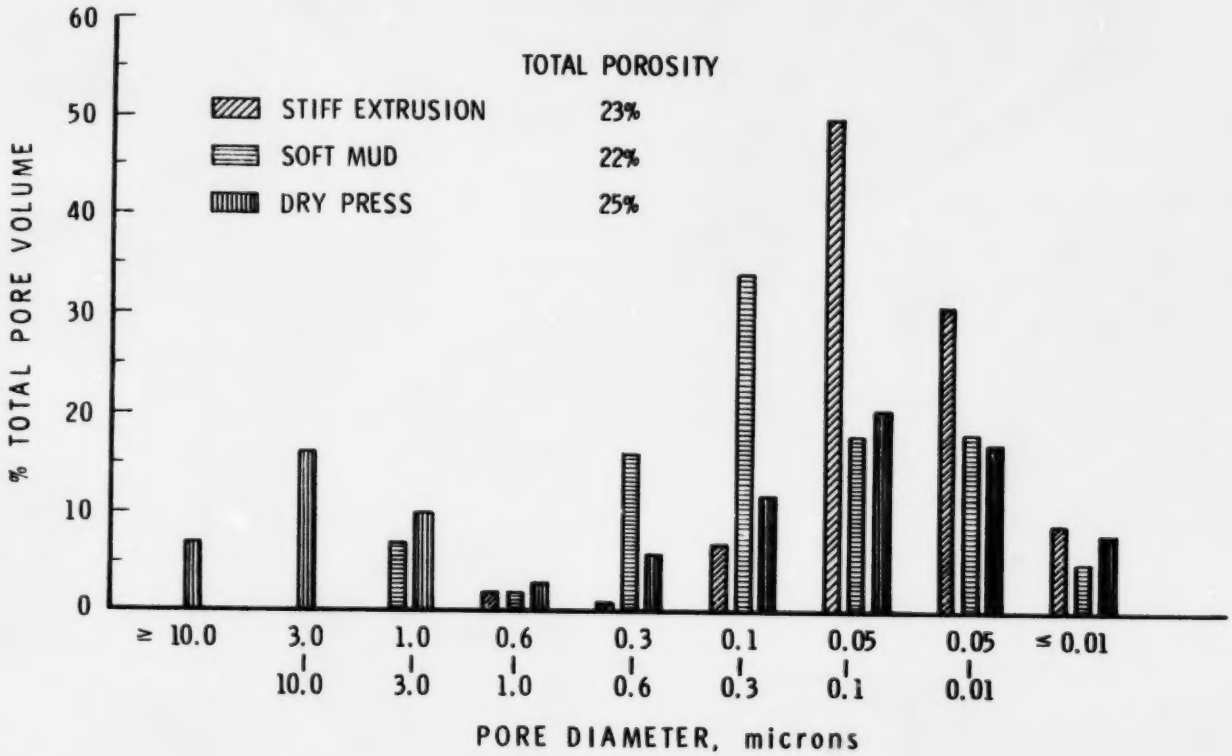

FIGURE 8

EFFECT OF MANUFACTURING METHOD ON PORE SIZE DISTRIBUTION OF FORMED GREEN BRICK

BR 6465-3

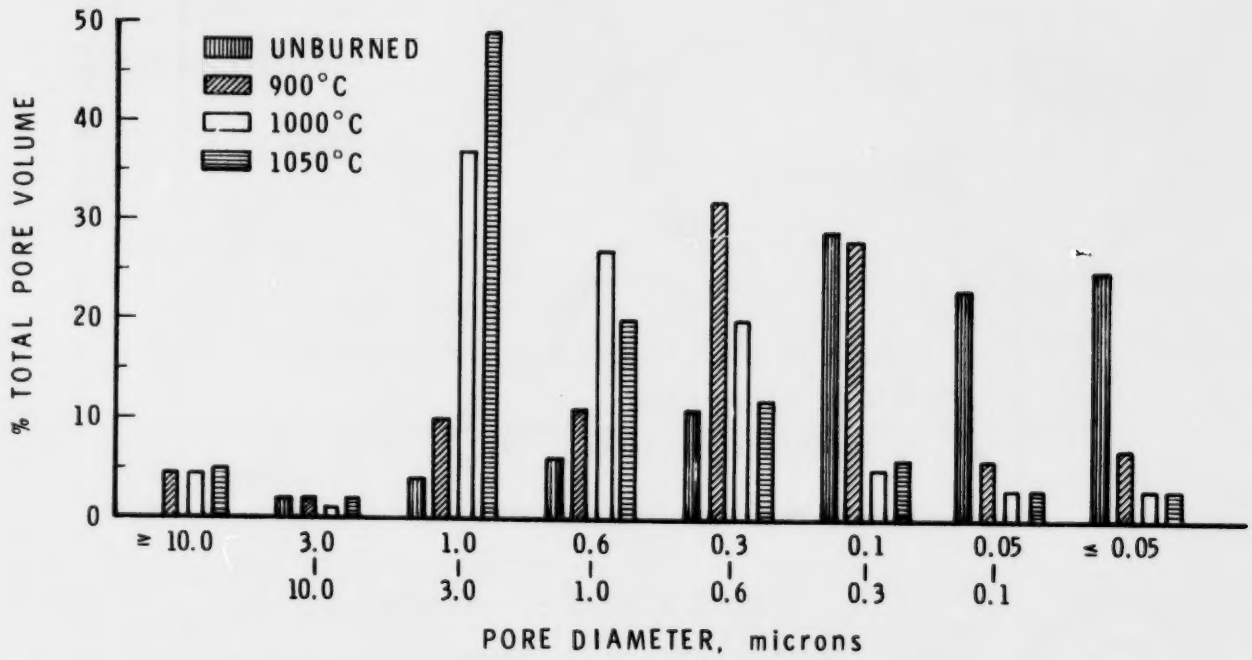

FIGURE 9

EFFECT OF FIRING TEMPERATURES ON PORE SIZE DISTRIBUTION

BR 6465-4

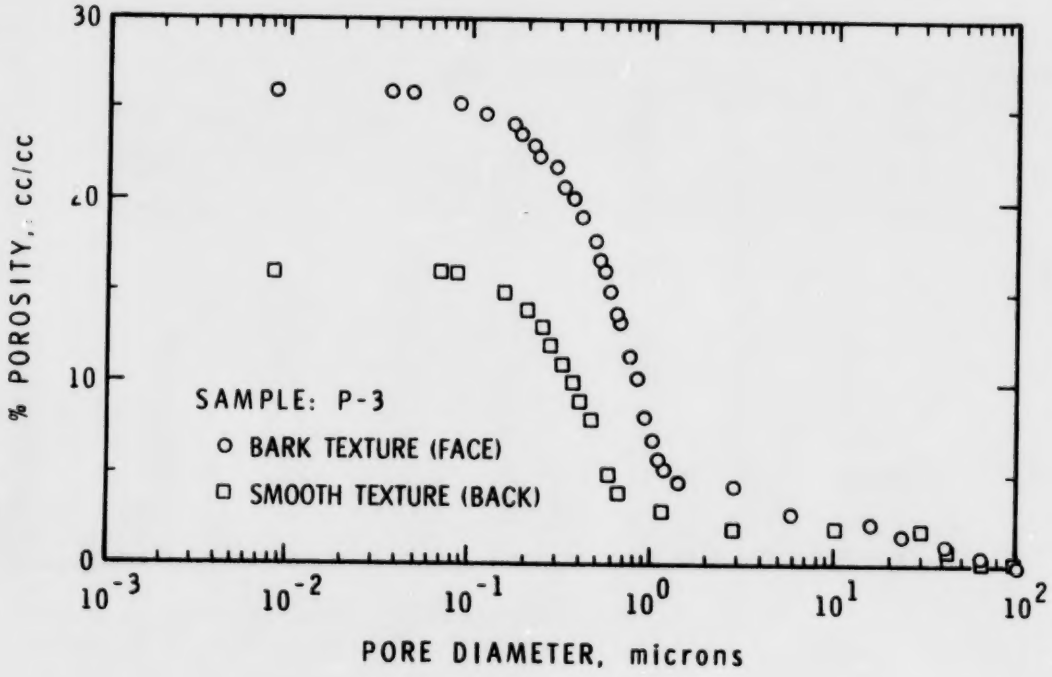

FIGURE 10

EFFECT OF BRICK TEXTURE ON PORE STRUCTURE DETERMINATION

BR 6265-2

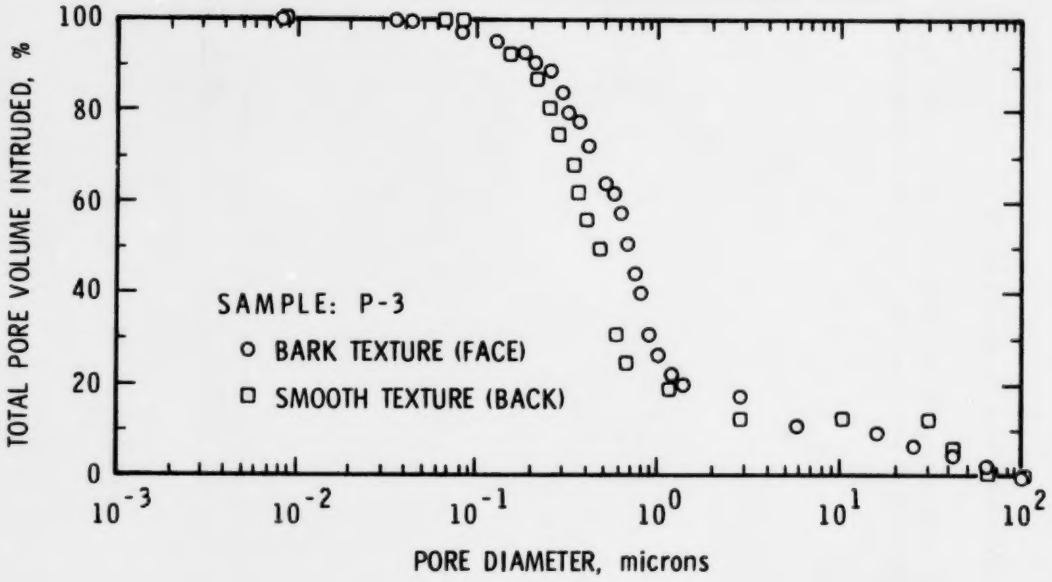

FIGURE 11

EFFECT OF BRICK TEXTURE ON PORE SIZE DISTRIBUTION

BR 6265-3

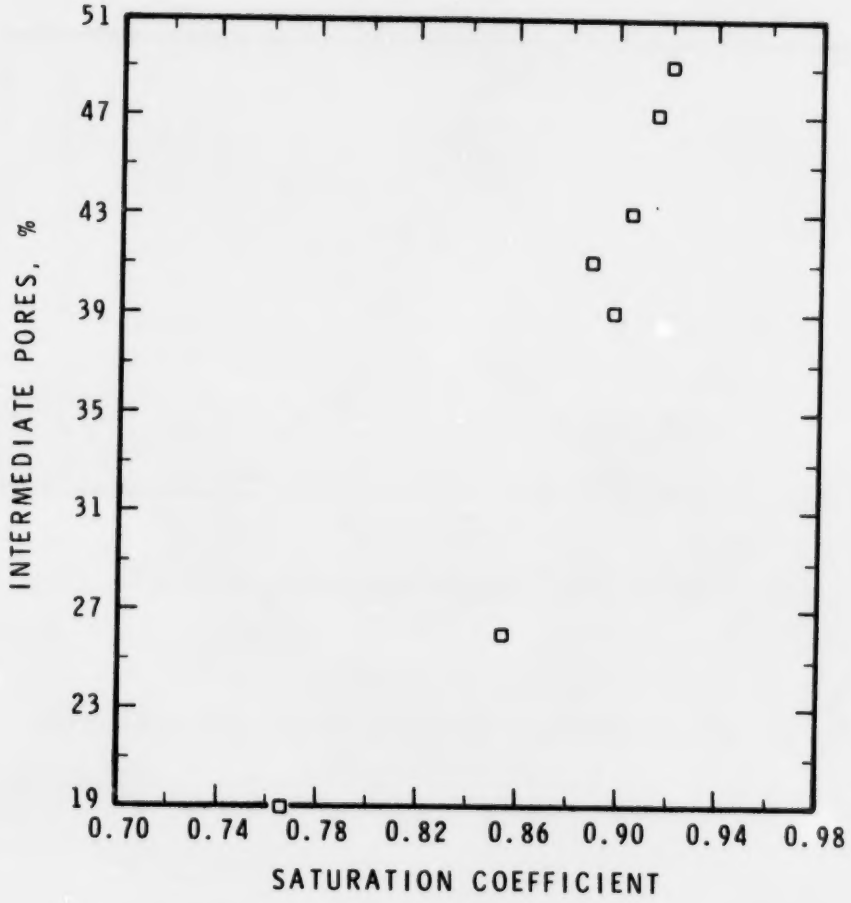

FIGURE 12

RELATIONSHIP BETWEEN THE AMOUNT OF INTERMEDIATE SIZE PORES AND SATURATION COEFFICIENT OF BRICKS FROM PROJECT BP

BR 6465-5

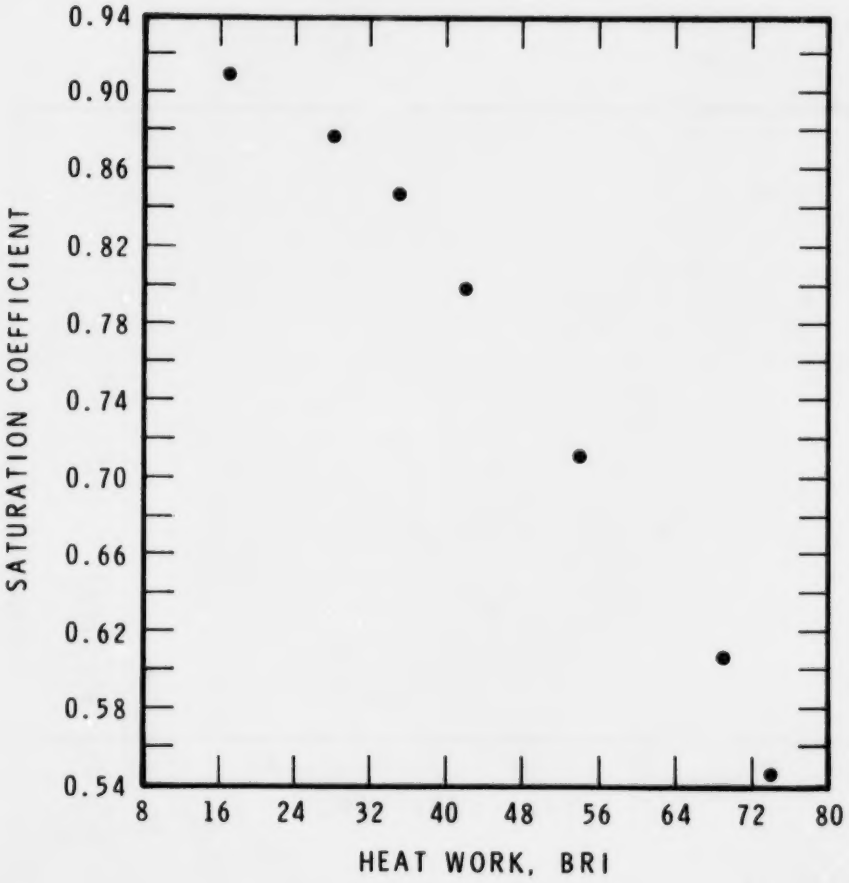

FIGURE 13

SATURATION COEFFICIENT OF BURNT BRICKS FROM PROJECT R AS A FUNCTION OF HEAT WORK

BR 6397-1

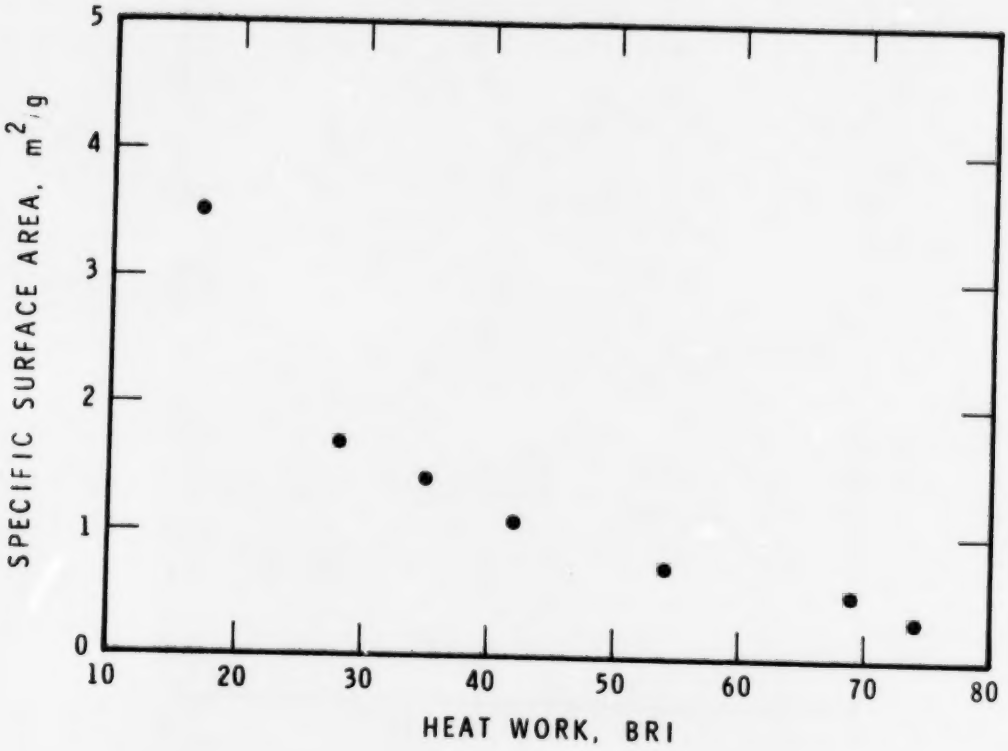

FIGURE 14

SPECIFIC SURFACE AREA OF BURNT BRICKS FROM PROJECT R AS A FUNCTION OF HEAT WORK

BR 6397-2

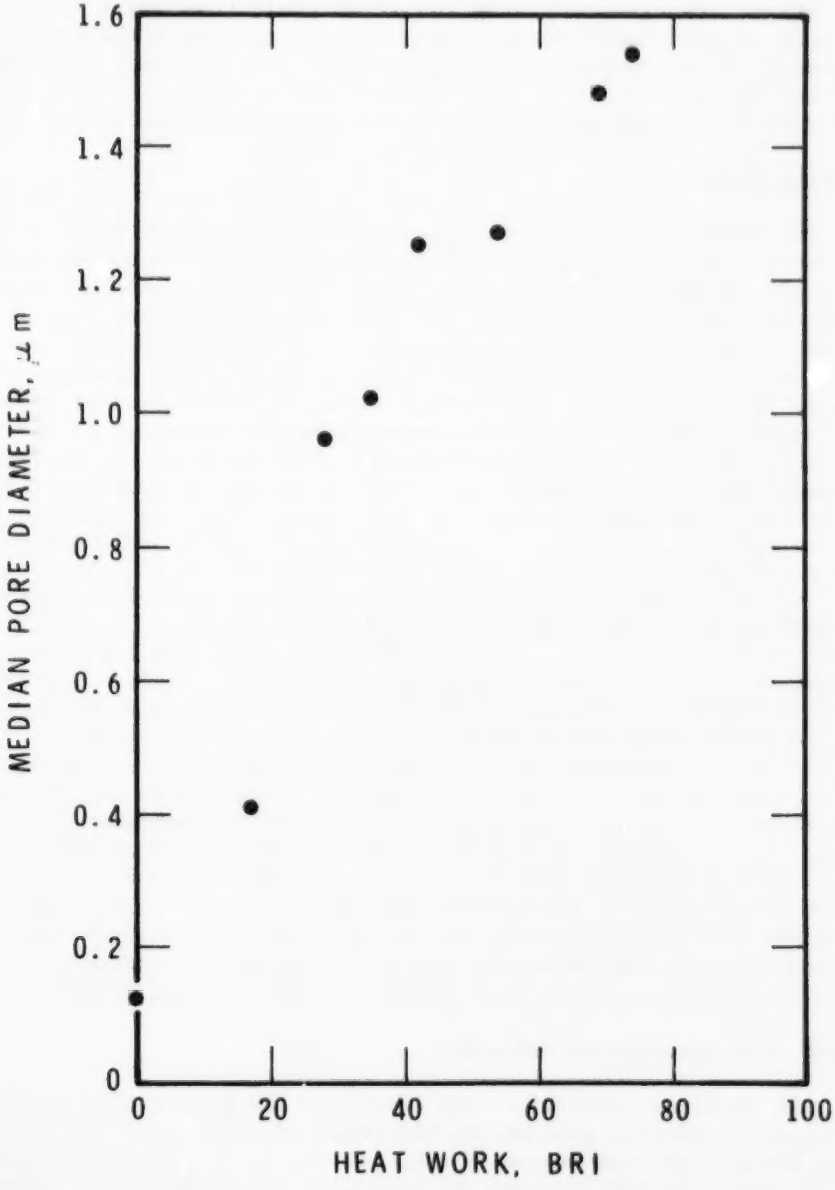

FIGURE 15

MEDIAN PORE DIAMETER OF BURNT BRICKS FROM PROJECT R AS A FUNCTION OF HEAT WORK

BR 6397-3

VI. DEVELOPMENT OF A DURABILITY TEST METHOD

The present test method for the assessment of frost resistance of clay bricks are time consuming and often yield inaccurate results.[4] The indirect methods based on pertinent durability properties are too dependent on the variation in raw material composition. It is desirable to establish a test method that is fast and reliable. One promising method is to measure expansion of a wet brick specimen during freezing.

Freezing Expansion

The proposed method involves measuring the expansion of a small vacuum-saturated brick specimen during one cycle of freezing and thawing and could be carried out in a few hours. It is assumed that the expansion is due to the stress developed by freezing the water and that the difference between freezing expansion and thawing shrinkage (called residual or irreversible expansion) is related to the damage suffered (Figure 16). The experimental results rated the samples of known relative durability in the proper order, as shown by the examples in Table 11. More meaningful results are presented in Figure 17 where the irreversible expansion is plotted against the total expansion on freezing for seventy-six bricks. The general trend is that higher freezing expansion is accompanied by larger irreversible expansion. This behaviour becomes more pronounced as the freezing expansion exceeds the 0.15% level. Since the total freezing expansion is much larger than the irreversible expansion, it would be more accurate to use the total freezing expansion to distinguish durable bricks from nondurable ones. The accuracy of the prediction, based on the freezing expansion test, varies from 100% identification of nondurable products with 15% rejection of possibly durable products by using 0.10% expansion as the threshold; to 93% correct prediction of nondurable products with a 2% rejection of possibly durable products by taking 0.15% as the threshold value. Even though it is best to measure total freezing expansion, in terms of experimental procedure it is more convenient to measure the irreversible expansion because then simple pins and gauges can be used for length measurement, since no in-situ monitoring is necessary. Measurements need only be taken before and after the freeze-thaw cycle. There is a reasonable correlation between the freezing expansion and the irreversible expansion, and such correlation was found to improve with larger specimen size.

Effect of Manufacturing Methods

The freezing expansion test also provided information on the effect of the manufacturing process on the frost resistance of the bricks. There is an indication that beyond a critical degree of saturation extruded clay bricks show a marked increase in freezing expansion whereas bricks made from the dry-press and soft-mud methods do not, as can be seen in Figure 18. Although frost susceptibility increases with degree of water saturation, regardless of the forming method, extruded bricks saturated above this critical level are potentially more susceptible to frost damage as shown by the increase in expansion. The common critical saturation

level lies between 75-80%. The cause for this behaviour in extruded bricks may be related to pore size distribution.

TABLE 11

COMPARISON OF THE FREEZING EXPANSION WITH FIELD PERFORMANCE

Brick	Freezing Expansion, %	Field Performance
A	0.033	Good
B	0.090	Good
C	0.210	Spalled
D	0.369	Spalled

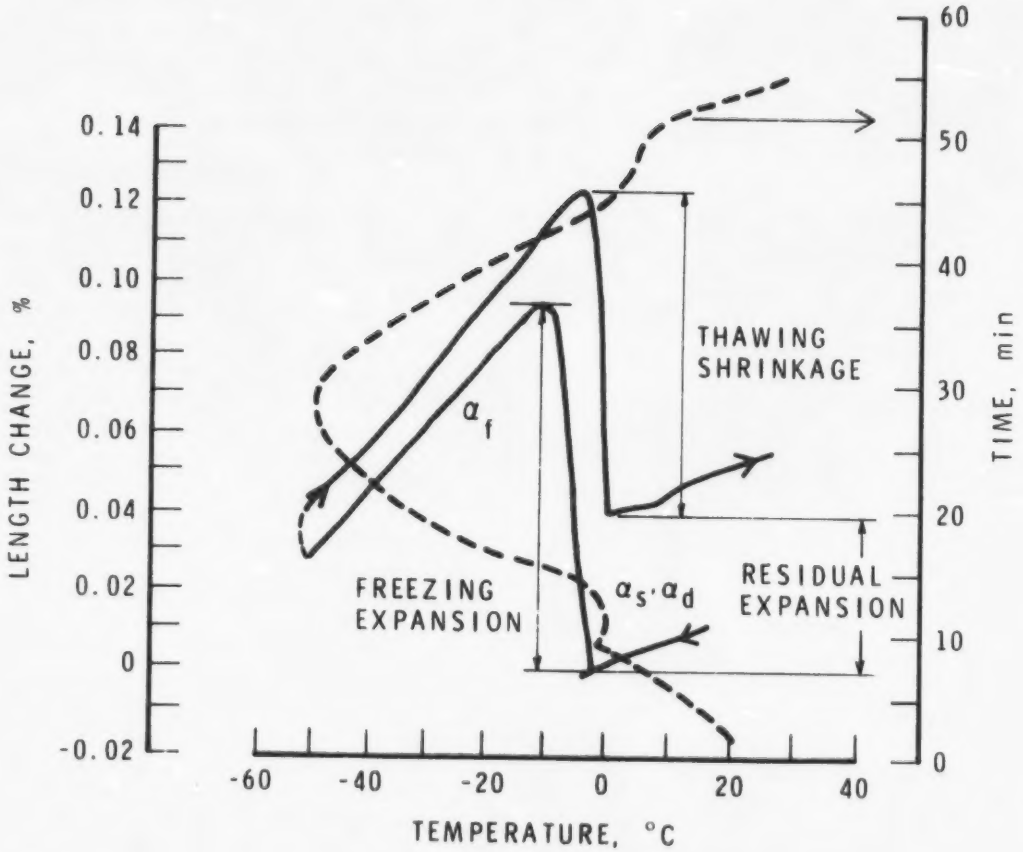

FIGURE 16

TYPICAL EXPERIMENTAL LENGTH CHANGE RESULTS FROM THERMOMECHANICAL MEASUREMENT

BR 6298-3

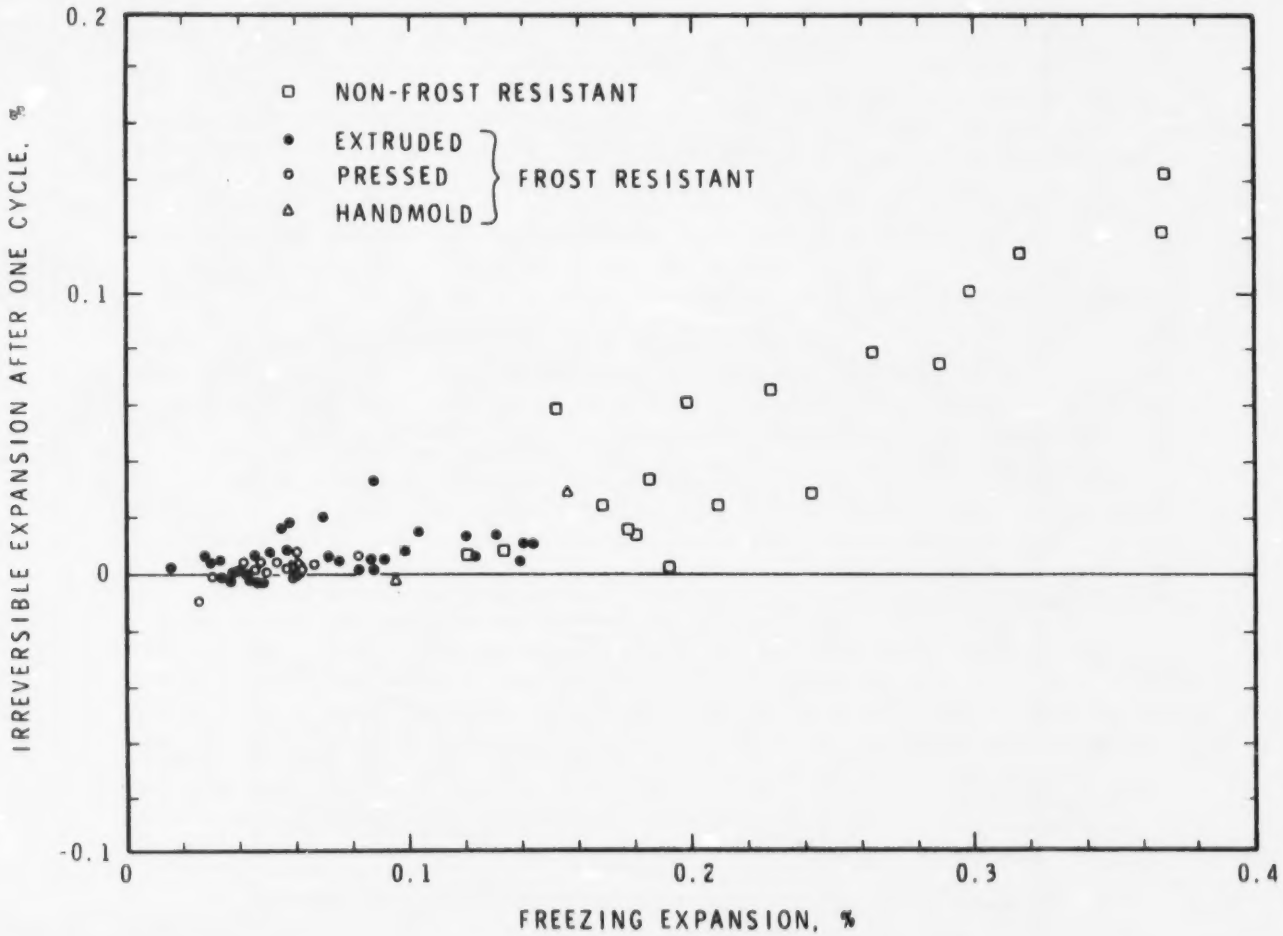

FIGURE 17

RELATIONSHIP BETWEEN IRREVERSIBLE EXPANSION AND FREEZING EXPANSION OF FROST RESISTANT AND NON-FROST RESISTANT BRICKS

BR 6465-11

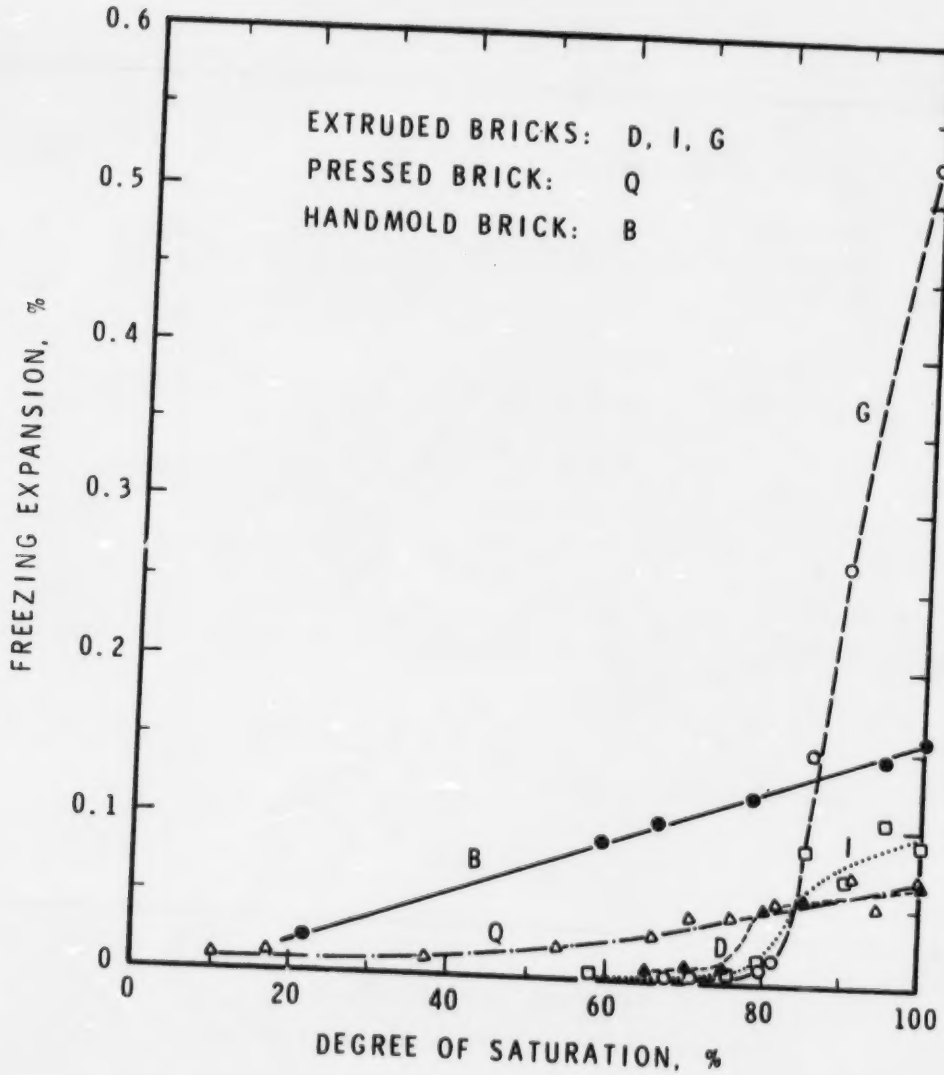

FIGURE 18

EFFECT OF MANUFACTURING METHODS ON FREEZING BEHAVIOR OF CLAY BRICKS

BR 6465-12

VII. OPTIMIZATION OF BRICK FIRING

Where frost durability is concerned, firing is the most important process in the production of clay bricks. Since frost resistance generally increases with greater heat work, it is advantageous for the industry to optimize the firing conditions. An empirical laboratory procedure capable of estimating the optimum heat work for a given brick was developed, based on saturation coefficient, specific surface area and the heat work. Some results from this test are presented in Figure 19. The method consists of plotting the specific surface areas of the laboratory-fired samples at different heat works versus the corresponding saturation coefficients. Graphically, the result could be described by two intersecting lines: one in the high saturation coefficient region where a large decrease in surface area is accompanied only by a small change in saturation coefficient; and the other at the low values of saturation coefficient where a small change in surface area is accompanied by a large reduction in saturation coefficient. In other words, the firing process at the initial stage reduces the surface area and properties related to it without greatly changing the saturation coefficient; at the later stage of firing the reverse occurs as saturation coefficient and properties related to it are more effectively improved, accompanied by smaller change in specific surface area. The optimum firing condition is approximately the heat work that corresponds to the intersection of the two lines. The optimum value is more clearly revealed by the derivative of the curve of specific surface with respect to saturation coefficient (Figure 20). The optimum would be the heat work corresponding to the region where the derivative tends to zero, i.e., little change in specific surface area with decrease in saturation coefficient. Using this procedure, the critical saturation coefficient, critical specific surface area and the critical heat work of the nine products were determined and are summarized in Table 12. The method could also be used to assess the intrinsic tolerance of a brickmaking material to frost action or to provide an indication as to how much improvement could be achieved in a product by modifying the present process. Results show that the degrees of improvement vary according to the raw materials. The procedure is simple and requires only a small number of samples.

The critical heat work of different bricks is correlated to a composition modulus which is the ratio of refractory components to the fluxes (Figure 21). In order to achieve certain frost resistance, brick with greater amounts of refractory components such as SiO_2, Al_2O_3 and CaO in a raw material, needs to be fired harder than a brick made of more fluxing components, such as the alkalies Na_2O and K_2O. The correlation, although not perfect, seems promising and warrants further research as a basis for predicting the critical heat work necessary for a brick just from its compositional analysis, including components such as FeO, Fe_2O_3 and MgO. This would further simplify the firing optimization procedure.

TABLE 12

CRITICAL VALUES FOR FROST DURABILITY BASED ON THE OPTIMIZATION PROCEDURE

Brick	Critical Saturation Coefficient	Critical Specific Surface m^2/g	Critical Heat Work, BRI
HC	0.84	0.9	69
R	0.85	1.4	32
UCS	0.83	1.6	40
BP	0.89	0.9	48
ZD	0.88	1.5	48
AZ	0.77	1.5	38
VD	0.76	2.0	50
RG	0.82	1.2	54
NW	0.84	1.1	-

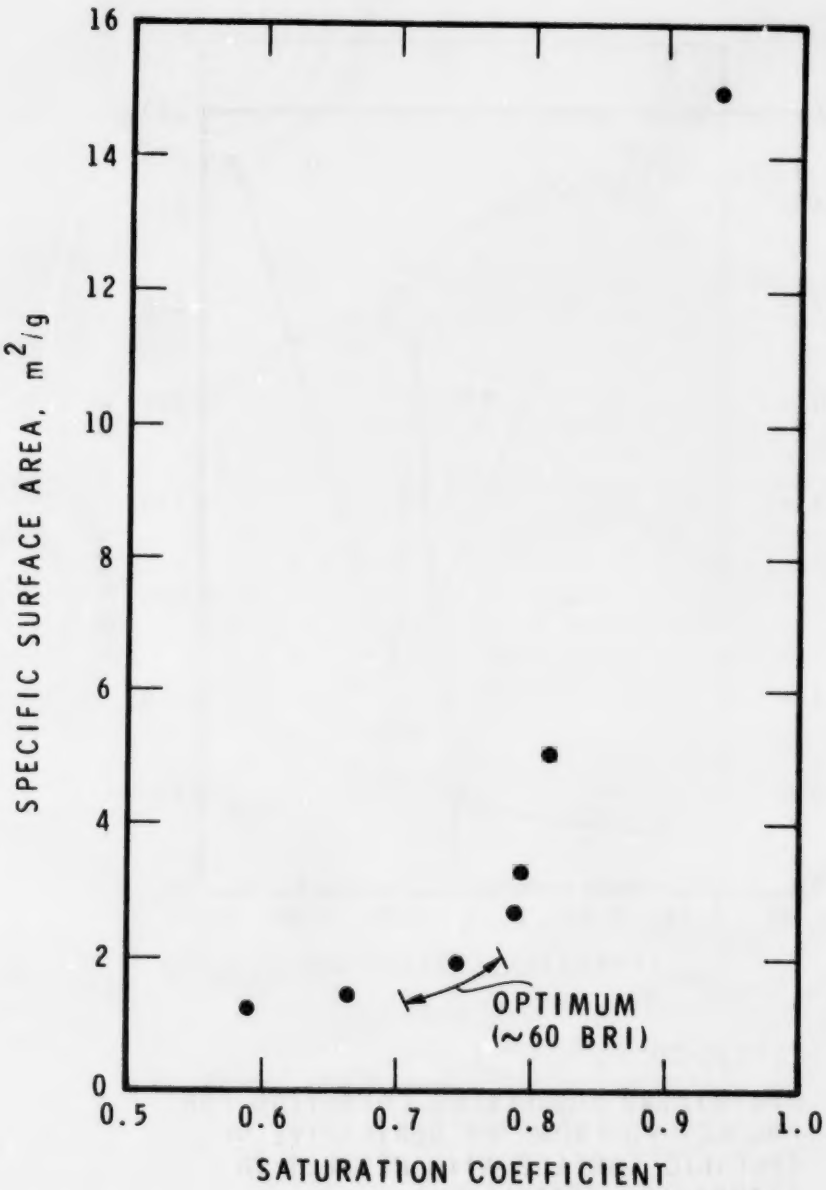

FIGURE 19

ESTIMATION OF OPTIMUM FIRING CONDITION FOR PROJECT VD BASED ON SPECIFIC SURFACE AREA AND SATURATION COEFFICIENT

BR 6397-4

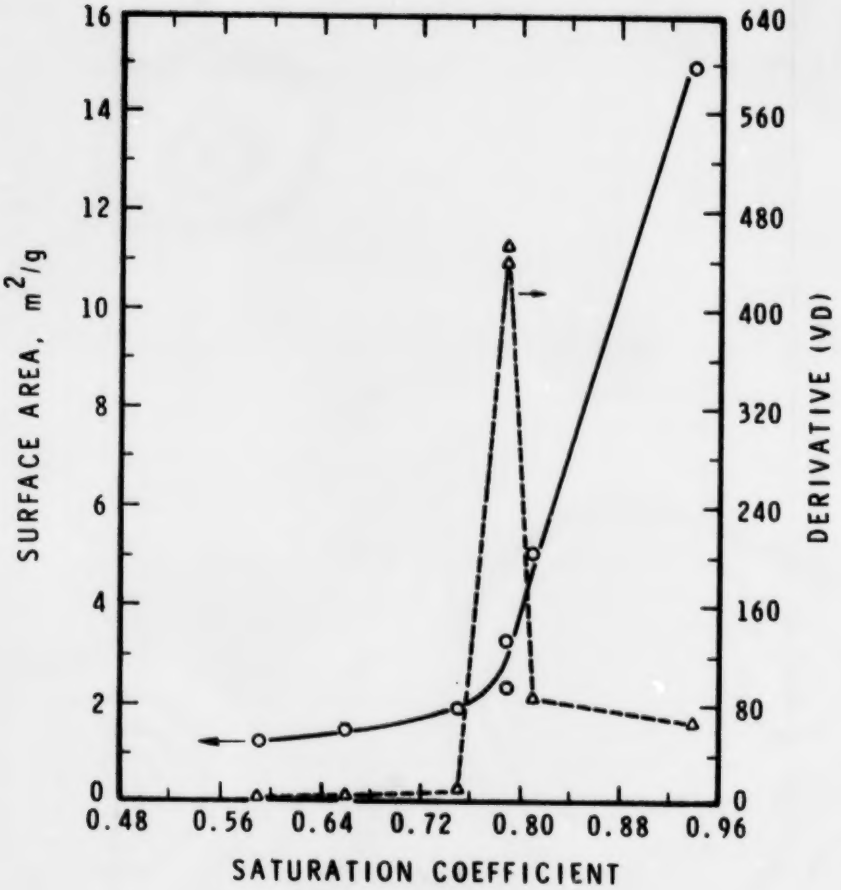

FIGURE 20

OPTIMIZING THE FIRING CONDITION FOR PROJECT VD FROM THE DERIVATIVE OF SPECIFIC SURFACE WITH RESPECT TO SATURATION COEFFICIENT

BR 6465-6

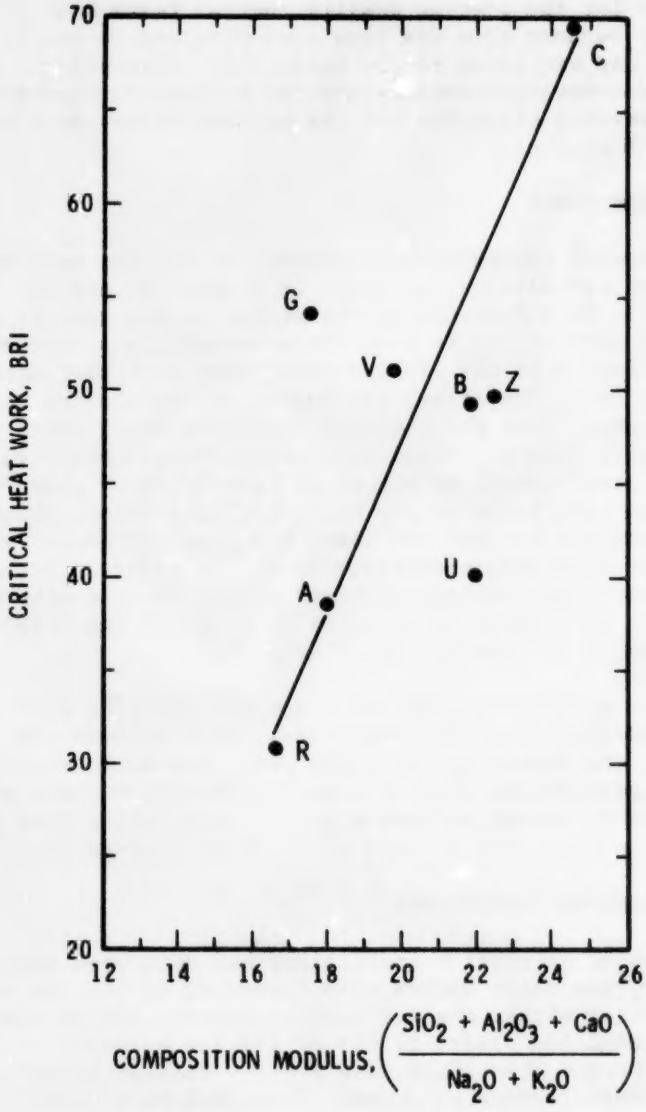

FIGURE 21

RELATIONSHIP BETWEEN THE CRITICAL HEAT WORK AND THE COMPOSITIONAL MODULUS

BR 6465-7

VIII. QUALITY CONTROL

The procedures for the present quality control tests have limitations, mainly because they are time consuming and do not take into account the day to day variation in raw materials. Absorption characteristics and saturation coefficient can be used for quality control purposes, but the maximum allowable and the optimum values must be established for each product.

Short-Term Absorption Tests

Correlation between the short-term absorption and the saturation coefficient has been established, as shown in Figures 22 and 23. The degree of correlation is a function of the mixing or homogeneity of the raw materials. The correlation is best where one single source of raw material is used (Figures 24 and 25) and worst when different materials are blended (Figure 26). Therefore, the degree of correlation reveals the homogeneity of the mix. Thus the standard quality control tests could be shortened considerably from the usual forty-eight hours (required in the case of saturation coefficient) to within an hour by using short-term absorptions, such as one-minute or one-hour cold absorption. These short-term absorption tests are carried out using the same procedures as the standard twenty-four-hour cold absorption test. In order to ensure best correlation, the short-term absorption tests should be done with half bricks or a fraction of a whole brick in order to avoid the "tight-skin effect" which increases the scattering of data.

Other potential quality control tests are the specific surface area and density measurements using the pycnometer. Both methods are sufficiently simple and practical for plant use. The measurement can be made in minutes. Although the initial rate of absorption could be measured in munites, it proved to have a poorer correlation than the short-term absorption tests and is more affected by surface texture.

Absorption and Saturation Coefficient

Cold absorption or saturation coefficient has been used separately for quality control, but their values vary depending on the raw material. The inadequacy of using either one for quality control can be seen from Figure 27. In a production plant, bricks of similar saturation coefficient but different absorption, and similar absorption but different saturation coefficient are both produced. These bricks have different properties. Thus it is recommended that absorption and saturation coefficient be used in conjunction, because the composite relation is like a "blueprint" of the brick.[5] This relationship between saturation coefficient and absorption not only reveals the quality of the particular brick produced but also the "history" of the brick, such as the original raw material composition and the firing condition as shown by Figure 28.

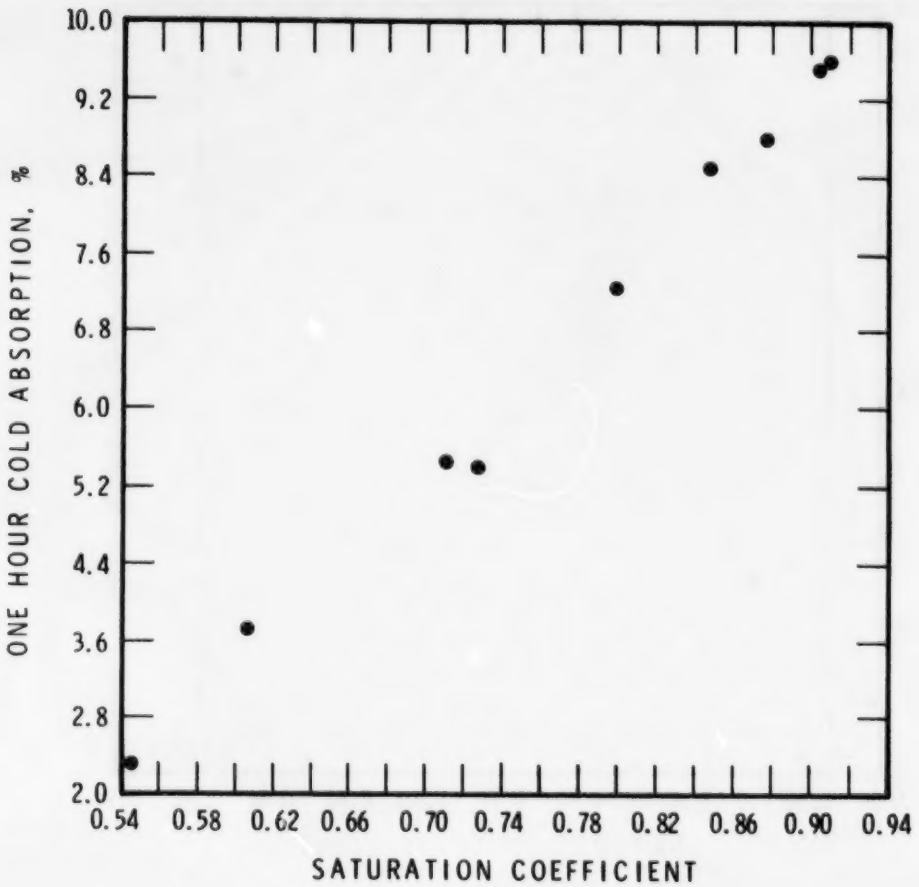

FIGURE 22

CORRELATION BETWEEN ONE HOUR COLD ABSORPTION AND SATURATION COEFFICIENT FOR BURNT BRICKS FROM PROJECT R

BR 6397-7

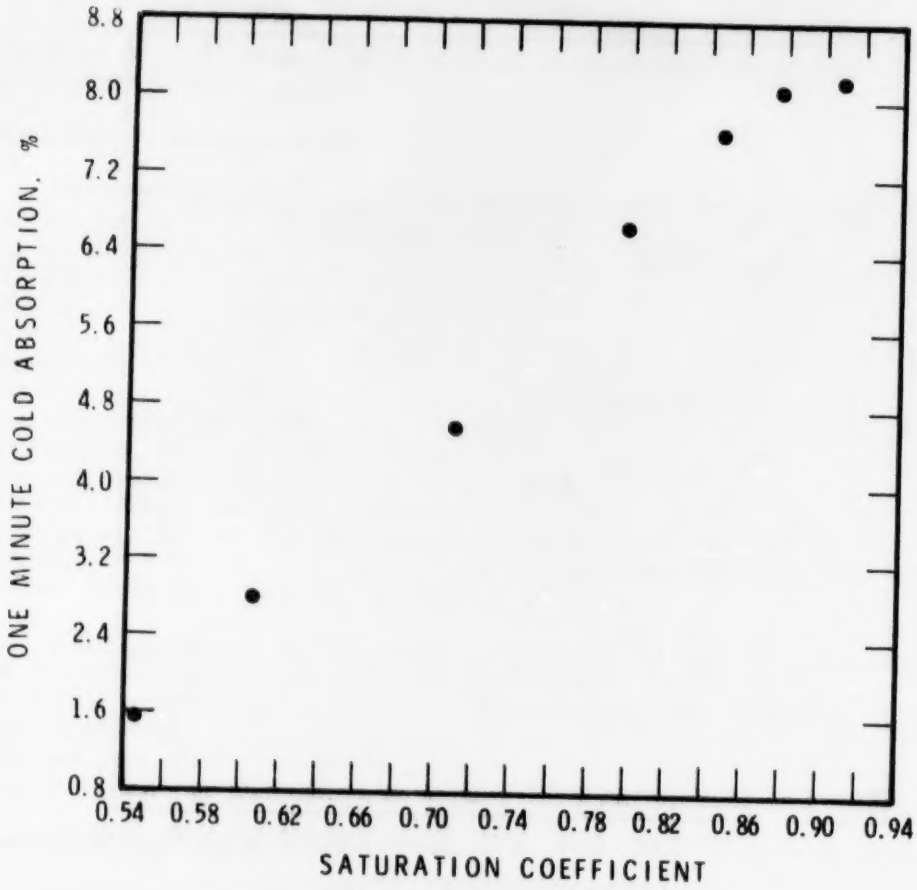

FIGURE 23

CORRELATION BETWEEN ONE MINUTE COLD ABSORPTION AND SATURATION COEFFICIENT FOR BURNT BRICKS FROM PROJECT R

BR 6397-6

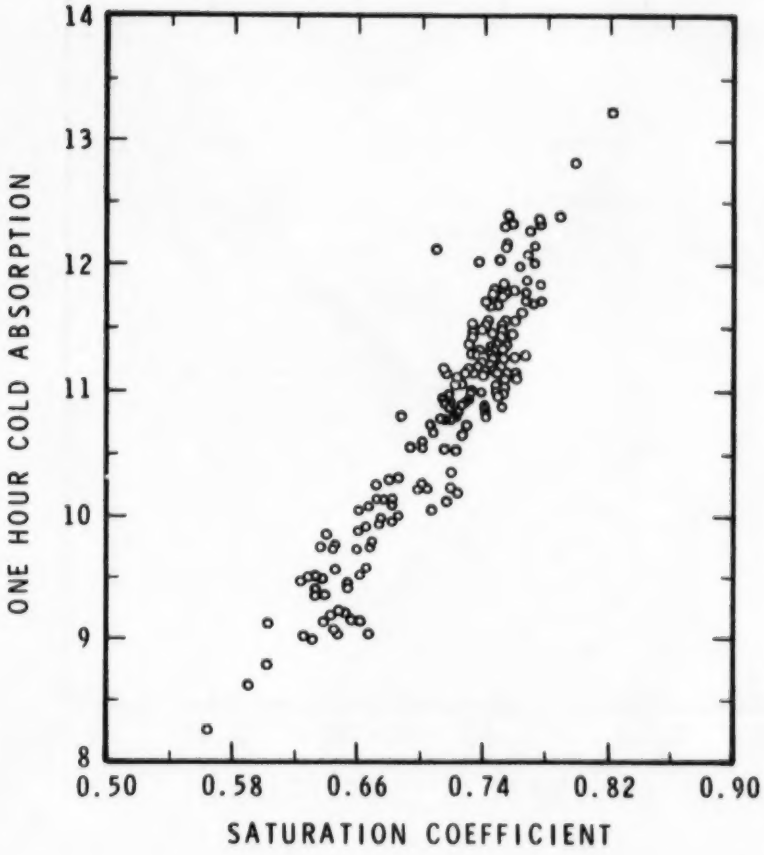

FIGURE 24

RELATIONSHIP BETWEEN SATURATION COEFFICIENT AND ABSORPTION OF BRICKS MADE FROM A SINGLE SOURCE OF RAW MATERIAL

BR 6465-8

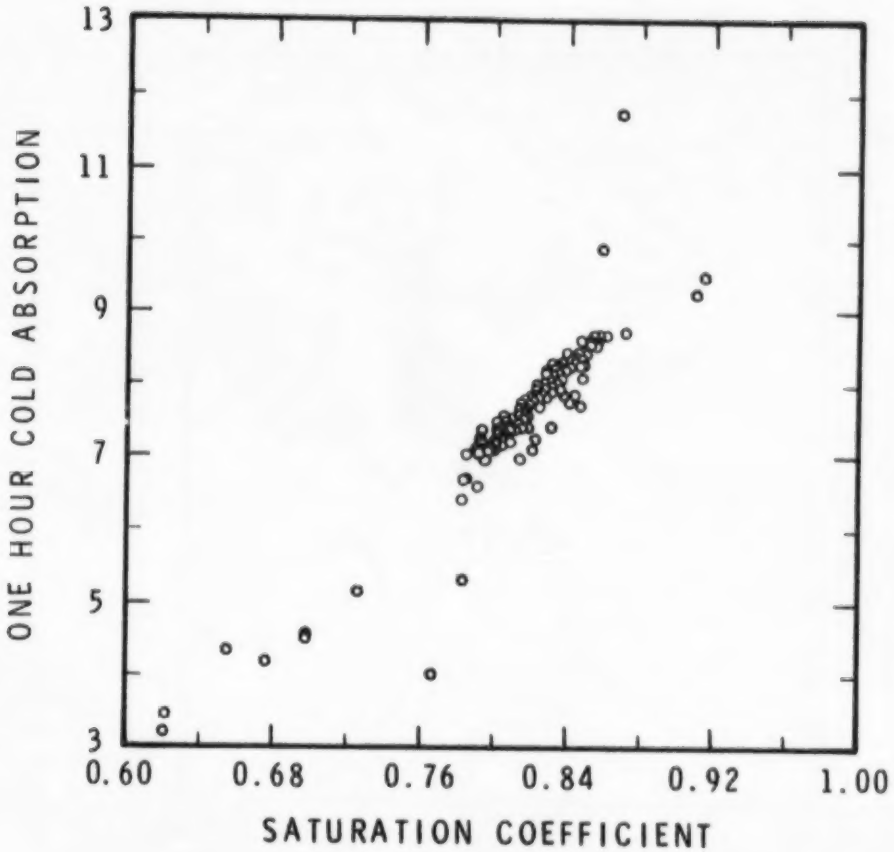

FIGURE 25

RELATIONSHIP BETWEEN SATURATION COEFFICIENT AND ABSORPTION OF BRICKS MADE WITH ADDITIVES INTRODUCED IN SLURRY

BR 6465-9

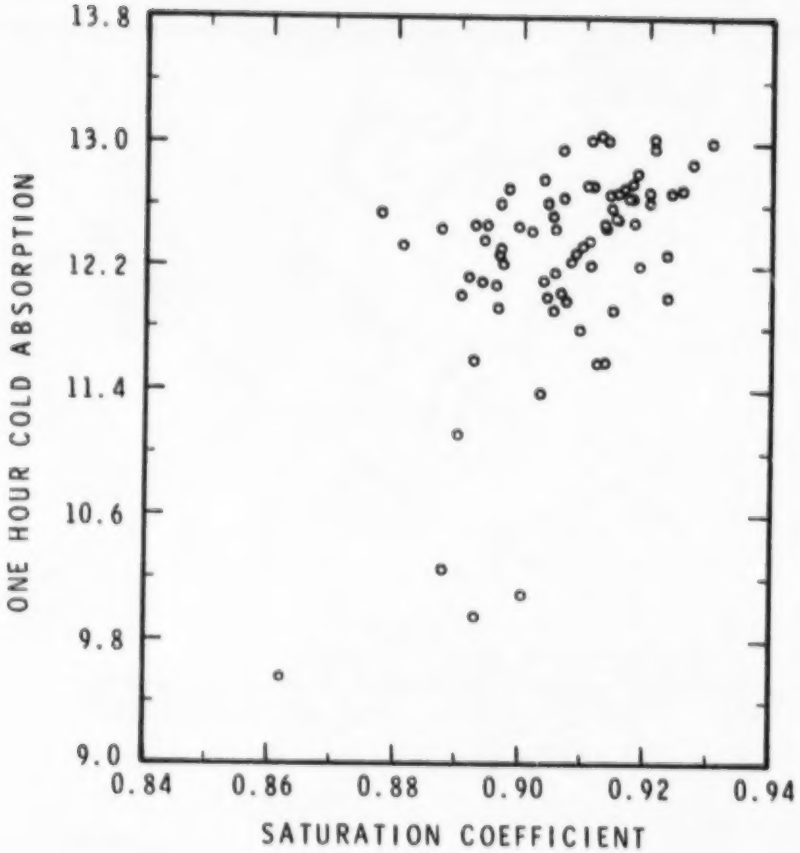

FIGURE 26

RELATIONSHIP BETWEEN SATURATION COEFFICIENT AND ABSORPTION OF BRICKS MADE FROM BLENDING A SHALE AND A CLAY

BR 6465-10

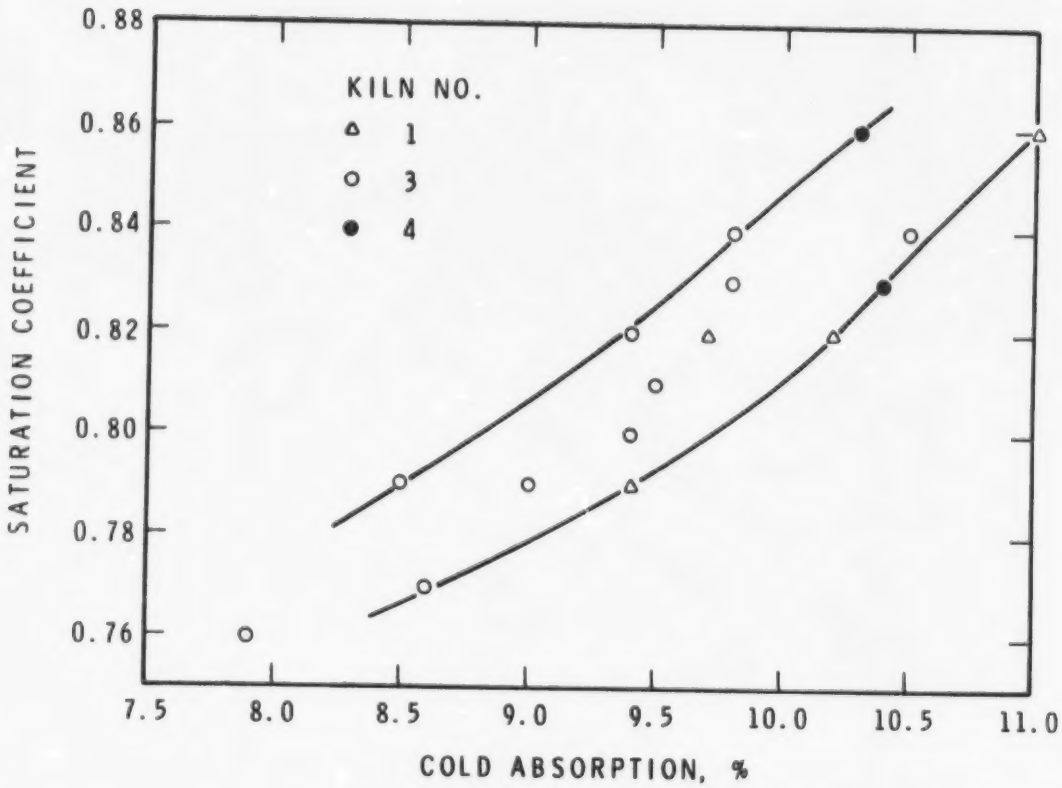

FIGURE 27

PROPERTIES OF BRICKS PRODUCED IN A PLANT OVER A PERIOD OF THREE MONTHS

BR 6193-23

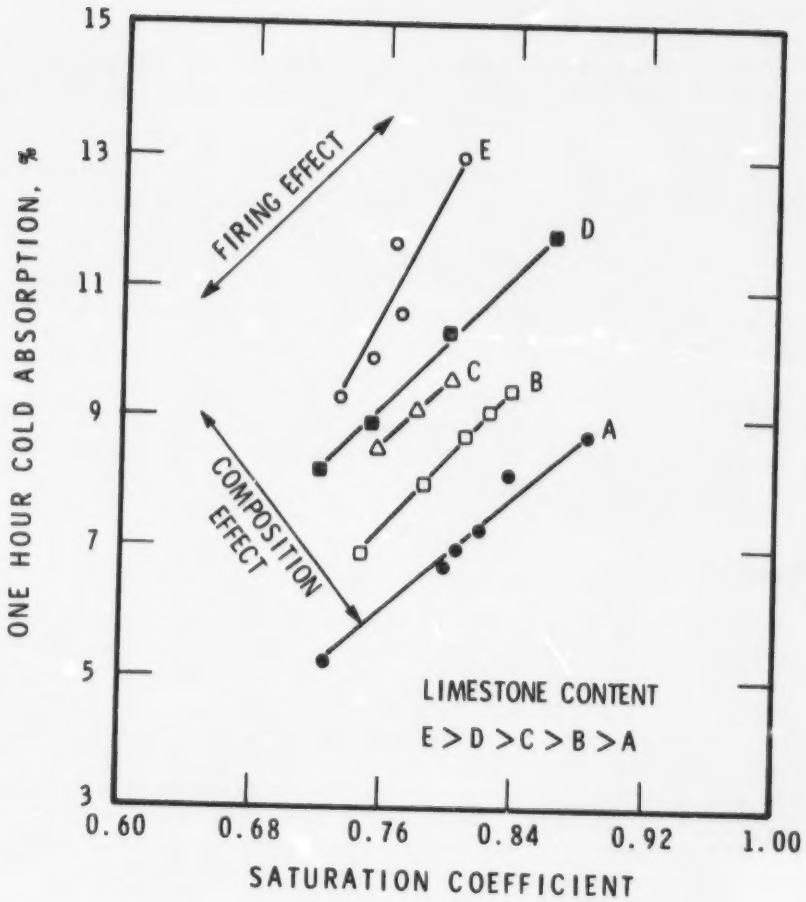

FIGURE 28

VARIATION IN RAW MATERIALS ELUCIDATED BY PLOTTING COLD ABSORPTION VS SATURATION COEFFICIENT

BR 6397-5

IX. CONCLUSIONS

- It is feasible, based on these studies, to carry out an economic and technical assessment of the industry's options for improvement of the durability of its various brick products.

- Using laboratory-fired model samples for tests, it is possible to determine the optimum conditions of firing for a given raw material to efficiently produce the most durable product.

- The existing test methods and criteria are inadequate to assess the durability of a brick product and, hence, the industry should consider new methods, such as those developed in this program, i.e., the new critical saturation coefficient or specific surface area, the freezing expansion test, the short-term absorption and the composite use of absorption and saturation coefficient, for quality control and for improving products.

- Numerous topics are worthy of further pursuit, namely, the simplification of the freezing expansion test, the relationship between the optimum firing condition and the raw material composition, the critical degree of saturation in extruded bricks and its cause, and the effect of silica and lime on durability of bricks.

Acknowledgement

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